Guidelines for Beamline Radiation Shielding Design at the National Synchrotron Light Source II

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1. NSLS-II RADIATION SHIELDING POLICY

Radiation exposure to staff and users as the result of National Synchrotron Light Source II (NSLS-II) operations must comply with Brookhaven National Laboratory (BNL) and Department of Energy (DOE) radiation requirements and must be maintained as low as reasonably achievable (ALARA). Per the Photon Science Shielding Policy (PS-C-ASD-POL-005), in continuously occupied areas during normal operation the dose rate is ALARA, and shall be < 0.5 mrem/h (based on an occupancy of 2000 hrs/year) or less than 1 rem in a year.

For a fault event, the dose rate in a non-radiation controlled area shall be < 20 mrem and < 100 mrem in a radiation controlled area. Although the experimental floor is initially designated as a radiation controlled area, it is hoped that in the future, it can be declared a non-radiation controlled area. As such, beamlines should be shielded such that in the event of a fault, the total dose, integrated over the duration of the fault, is < 20 mrem.

In this guideline, the recommended shielding are based on calculations (see Appendix) to achieve dose rates < 0.05 mrem/hr in continuously occupied areas during normal operations.

The purpose of this document is to provide guidelines for the design of radiation shielding at National Synchrotron Light Source II (NSLS-II) beamlines. This guideline is based on the current suite of insertion devices and optics, and assumes generic beamlines with shielding enclosures of certain sizes and considers scattering from typical beamline components. For beamines that are significantly different, additional calculations may be needed.

2. RADIATION SOURCE PARAMETERS AND SHIELDING DESIGN SIMULATIONS

Beamlines are required to shield against two primary sources of radiation, the primary gas bremsstrahlung and the synchrotron beam, and, the secondary radiation that comes from scattering of these two primary beams off beamline components and/or air. In this document, secondary bremsstrahlung refers to the scattered primary gas bremsstrahlung from any component. Tables 2-1 and 2-2 list the radiation source parameters used in developing this guideline.

Table 2-1: NSLS-II primary gas bremsstrahlung source parameters

Electron energy	3 GeV
Stored current	500 mA
Length of ID straight section	15.5 m
Length of BM and 3PW straight section	6.6 m
Pressure in straight section	1 ntorr

Table 2-2: NSLS-II synchrotron beam source parameters considered in this guideline

Source	Period (mm)	Length (m)	Beff (T)	No. of periods

DW100	100	7	1.8	70
IVU20	20	3	1.03	148
EPU45 (L-mode)	45	4	1.03	89
BM	-	2.6	0.4	1
3PW	-	0.25	1.12	1

Shielding guidelines for the beamlines have been developed through extensive simulations using the EGS41, FLUKA2, and STAC83 computer programs. The contact dose rates have been calculated at the external surface of the beamline enclosure shield panels or beam transport pipes. The detailed methodology and results for these calculations, which form the basis of these guidelines, are provided in the Appendix or are referenced to previous publications.

3. GENERAL PERSONNEL PROTECTION SYSTEMS GUIDELINES

Beamline radiation shielding falls under the broader umbrella of Personnel Protection Systems (PPS). The following are guidelines that apply to many of the components discussed in this document.

- All shielding that can be moved during normal operations, such as manual stops, shutters or doors, require redundant PPS-interlocked switches. Remotely controlled shutters have two independent shielding blocks, each of which are thick enough to provide sufficient shielding.

- All shielding that do not move during normal operations such as enclosure panels and fixed collimators/stops, shall be secured and placed under configuration control.

- On the beamline, all components that serve to ensure the integrity of radiation shielding, such as upstream masks or thermal beam stops are considered PPS components. In the case of water-cooled masks/stops that protect radiation shielding, the water flow to these components shall be monitored by the PPS with redundant flow monitors

- On some beamlines, the vacuum may play a role in radiation safety. For example, in soft-x-ray beamlines, it may be adequate that no one can place any part of their body directly in the beam within an evacuated chamber. In these cases, redundant SIL-3 rated vacuum interlock switches whose statuses are monitored by PPS may be used.

- Note that all PPS-interlocked switches need to be tested at intervals specified in the BNL Radiological Control Manual. Thus, judicious use of PPS-interlocked switches is advised.

4. THERMAL MANAGEMENT

Radiation shielding is usually not actively cooled and thus, cannot tolerate a thermal load. As such, it is imperative that the power in the incident beam be removed upstream, before it hits the shielding. In most cases, this is achieved with upstream water-cooled copper masks or stops. The masks or stops must be large enough to safely intercept the full angular and spatial range of the incident beam. Water flow needed to ensure the integrity of synchrotron beam masks and stops must be monitored by the PPS. Careful attention must be given to high-power stray beams from misaligned optics. In some cases, it may be necessary to limit the range of x-ray optics (eg, mirror angles and translations) so that the downstream masks and stops do not become too large. Such limits on x-ray optics have to meet PPS requirements.

5. RAY TRACES

Ray traces are a critical part of the radiation shielding design process. The front-end and beamline ray trace procedures are given in PS-C-ASD-PRC-147 and PS-C-XFD-PRC-008 respectively. For safety reviews, the NSLS-II requires the following set of ray traces:

- Synchrotron ray traces. These ray traces show the envelope of synchrotron rays and ensure that the thermal power of the synchrotron white-beam is safely captured.

- Primary bremsstrahlung ray traces. These ray traces show the envelope of the primary gas bremsstrahlung and ensure that they are safely captured.

In addition, the following ray traces may be useful:

- High power reflected beam ray traces. In many cases, the reflected beam from a beamline optic can have significant power and can damage shielding. These ray traces are one way to ensure that all rays with significant power from the allowable (physically or within configuration control) parameter space of the optic are safely captured. Note that in addition to stopping the thermal power in the reflected beam, it is also necessary to stop the radiation.

- Secondary bremsstrahlung ray traces. These are useful for the design of the secondary bremsstrahlung shielding (see section 9). These ray traces ensure that there is adequate shielding coverage for the radiation that results from the primary gas bremsstrahlung scattering off beamline components.

6. GUIDELINES FOR STOPS, COLLIMATORS AND SHUTTERS

6.1 Primary bremsstrahlung stops, collimators and white beam shutters

These components are used to stop or collimate the primary bremsstrahlung. White beam shutters have to stop both the synchrotron beam and the primary bremsstrahlung; but at the NSLS-II, the radiation shielding requirements are dominated by the bremsstrahlung.

Guidelines and assumptions:

- The minimum thickness, along the beam direction, for primary bremsstrahlung stops, collimators and white beam shutters for all NSLS-II beamlines is 30 cm of Pb or 20 cm of W.

- Lateral dimensions for these components shall be based on ray tracings. Distance between lateral edge and the extremal bremsstrahlung ray shall be > 24 mm for tungsten and > 37.5 mm for lead. These are the 3-Moliere-radius distances for tungsten and lead respectively. In most cases, it will be useful to extend the lateral dimensions of these components in order to help manage the secondary bremsstrahlung (see Section 9).

- The primary bremsstrahlung stops, collimators, and white beam shutters shall be located inside a white beam enclosure as described in Section 7.

- White beam shutter status (open or close) shall be monitored by redundant PPS-interlocked switches and shall be designed to be fail-safe.

- If the shielding is made from smaller bricks, the bricks shall be properly staggered so that the edges and seams are not aligned.

Basis: LT-ESH-STD_001

6.2 Integral primary bremsstrahlung stop with pink/monochromatic beam apertures

In many cases, the monochromatic/pink beam may not be sufficiently separated from the primary bremsstrahlung cone; that is, the closest extremal ray of the primary bremsstrahlung cone to the monochromatic/pink beam aperture is less than 3 Moliere radius. In these cases, an integral primary bremsstrahlung stop with a pink/monochromatic beam aperture can be employed.

Guidelines and assumptions:

- The monochromatic/pink beam aperture is < 2 cm^2.

- For all NSLS-II beamlines, the edge of the aperture shall be > 10 mm from the closest extremal bremsstrahlung ray. This minimum distance is the same for both Pb and W components. There must be material at the ‘far side’ of the aperture so that the total amount of material in all lateral directions is at least 3 Moliere radii (37.5 mm for Pb and 24 mm for W) from the extremal bremsstrahlung rays .

- The minimum thickness, along the beam direction, for these components for all NSLS-II beamlines is 30 cm of Pb or 20 cm of W.

- The integral primary bremsstrahlung stop with pink/monochromatic beam aperture shall be located inside a white beam enclosure as described in Section 7.

Basis: Appendix 6.2

6.3 Pink beam shutters/stops

Pink beam shutter requirements are driven by secondary bremsstrahlung scattered from the white beam optic. Because the secondary bremsstrahlung spectrum changes significantly as a function of scattering angle and the scatterer, the shielding needed to stop the secondary bremsstrahlung varies greatly. Currently, no specific guidelines on this are provided, and calculations will have to be done on a case-by-case basis as needed. However, it should be noted that the white beam shutter/stop (see 6.1) is a conservative solution for this application.

6.4 Monochromatic beam shutters/stops

The shielding requirements for monochromatic beam shutters/stops depend on the parameters of the incident monochromatic beam. However, in terms of maintenance and control, there is an advantage to having identical monochromatic shutters within NSLS-II. As such, the recommended monochromatic beam shutter specifications for NSLS-II are given in LT-C-XFD-SPC-PSH-001. It uses two 19 mm thick W blocks to stop the beam. The W thickness is conservatively based on the DW100 source with a 0.5% monochromatic beam bandwidth. In addition, the design, with its large aperture blocks has been shown to be useful in mitigating any secondary bremsstrahlung in the vicinity of the monochromatic beam (see Section 9).

Monochromatic beam stops are required at the end of monochromatic beam enclosures to stop the incident beam and some of the forward scattered beam. They are needed because the monochromatic beam enclosures (see Section 7.2) are only shielded for scattered radiation, and not the direct incident beam. Assuming a 0.1% monochromatic beam bandwidth, the size and thickness of the monochromatic beam stops for various NSLS-II sources are given in Table 6.4-1.

Table 6.4-1: Recommended monochromatic beam stops

Beamline source	Mono beam stop

DW100	50 cm x 50 cm x 2 cm Pb
IVU20	50 cm x 50 cm x 1.4 cm Pb
EPU45	50 cm x 50 cm x 1.4 cm Pb
3PW	50 cm x 50 cm x 1.2 cm Pb
BM	1 mm Pb; Forward scattering negligible, size determined by ray trace

Basis: LT-C-ESH-STD-001 and Appendix 6.4

7. GUIDELINES FOR SHIELDED ENCLOSURES

Recommended shielding for enclosures are based on scattering of the incident radiation by copper or silicon.

7.1 White beam enclosures (or First Optical Enclosures)

At NSLS-II the white beam enclosure shielding requirements are dominated by the scattering of the primary gas bremsstrahlung and not the synchrotron beam. The recommended shielding for lateral and roof panels are sufficient for these scatterers in the enclosure and should cover most white beam component configurations. However, the recommended shielding for the downstream panels may not be sufficient to protect against secondary bremsstrahlung. In these cases, additional shielding against secondary bremsstrahlung for the downstream panel will be needed (see Section 9).

<u>Guidelines and assumptions:</u>

- For ID beamlines, the lateral panel of the enclosure is ≥ 1.0 m from the white beam. The roof is ≥ 1.5 m above white beam height. The length of the enclosure is assumed to be 10 m.

- For BM/3PW beamlines, the lateral panel of the enclosure is ≥ 0.65 m from the white beam. The roof is ≥ 1.5 m above the white beam height. The length of the enclosure is assumed to be 10 m.

- The primary bremsstrahlung shall be stopped upstream of the white beam enclosure downstream panel or, in the case of multiple white beam enclosures, shall be transported downstream without hitting any enclosure panels or beam transport pipes.

- The recommended whiten beam enclosure shielding is given In Table 7.1-1.

Table 7.1-1: Recommended shielding for white beam enclosures

Beamline source	Lateral panel (Pb)	Roof panel (Pb)	Downstream panel (Pb)
All ID sections	18 mm	10 mm	50 mm
BM/3PW	18 mm	4 mm	50 mm

Basis: LT-ESH-STD_001 and Appendix 7.1

7.2 Monochromatic beam enclosures

The shielding requirements for monochromatic beam enclosures depend on the parameters of the incident monochromatic beam. NSLS-II TN145 provides a series of plots that can be used to determine the shielding requirements for specific monochromatic beam parameters. It is highly recommended that users design the shielding conservatively so that the enclosure can accommodate possible future scientific scope changes.

Here, general guidelines are provided for monochromatic beam enclosures assuming a perfect Si(111) monochromator with maximum energy of 30 keV.

<u>Guidelines and assumptions:</u>

- These guidelines are based on a 3 m (W) x 3 m (H) x 10 m (L) enclosure with the scatterer in the middle.

- Guidelines are based on monochromatic beams from a perfect Si(111) monochromator with maximum energy of 30 keV. The dose contributions from (333), (444), (555) and (777) harmonics are included.

- All primary and secondary bremsstrahlung shall be stopped upstream of the enclosure.

- A monochromatic beam stop (see section 6.4) shall be installed on the downstream wall.

- A 10% occupancy on the roof is assumed for the recommended shielding. If this is not true, the roof thickness shall be the same as the lateral wall thickness.

- The recommended monochromatic enclosure shielding is given in Table 7.2-1.

Table 7.2-1: The recommended shielding for the monochromatic/pink beam enclosures

Beamline source	Lateral & upstream walls	Roof	Downstream panels
DW100	4 mm Pb	3 mm Pb	7 mm Pb
IVU20	6 mm Fe	3 mm Fe	11 mm Fe
EPU45	6 mm Fe	3 mm Fe	11 mm Fe
3PW	3 mm Fe	2 mm Fe	6 mm Fe
BM	1 mm Fe	1 mm Fe	2 mm Fe

Basis: TN 145 and LT-C-ESH-STD-001.

7.3 Pink beam enclosures

In most cases, pink beam (assuming 30-50 keV cut-off) enclosures with similar dimensions as monochromatic beam enclosures given in Section 7.2, have the same shielding requirements as the monochromatic beam enclosures. However, because the pink beam is collinear with secondary bremsstrahlung, more shielding will be required to stop the direct/forward scattered pink beam. Since the required shielding to stop secondary bremsstrahlung is dependent on the scattering angle and the mirror dimensions, a case-by-case simulation will be required to determine the dimensions of the pink beam (and secondary bremsstrahlung) stop.

8 GUIDELINES FOR BEAM TRANSPORTS

In normal operations, beam transports are assumed to be under vacuum. Air in the transport pipe is considered a fault condition. In this guideline, the shielding recommendations given for air in the transport pipe limits the dose rates to < 0.5 mrem/hr. A solid scatterer in the beam within the transport pipe, such as a diagnostic flag, is considered normal operations and the dose rate goals are < 0.05 mrem/hr.

8.1 Monochromatic beam transport

These guidelines only apply to monochromatic beam transport. Calculations were performed at 22 keV, 66 keV, 87.5 keV, 110 keV and 154 keV, and a 0.1% monochromatic beam bandwidth is assumed.

<u>Guidelines and assumptions</u>

- All primary and secondary bremsstrahlung shall be stopped upstream of the monochromatic beam transport.

- The transport pipe is made from stainless steel with wall thickness ≥ 1 mm.

- The monochromatic beam is ≥ 25 mm from the inside wall of the pipe.
- The monochromatic beam shall not hit the transport pipe.
- The recommended monochromatic beam transport shielding is given In Table 8.1-1.

Table 8.1-1: Recommended shielding for monochromatic beam transport

Beamline source	Shielding required for < 0.5 mrem/hr due to complete vacuum loss in the beam transport	Shielding required locally on beam transport for < 0.05 mrem/hr for a solid scatterer
DW100	5 mm Pb	12 mm Pb
EPU45	3 mm Pb	7.0 mm Pb
IVU20	3 mm Pb	7.0 mm Pb
3PW	2 mm Pb	5.0 mm Pb
BM	1 mm Fe	1.0 mm Fe

Basis: Appendix 8.1

8.2 Pink beam transport

The challenge in pink beam transports is with the secondary bremsstrahlung that is collinear with the pink beam. Since the secondary bremsstrahlung spectrum depends on the scatterer and the angle, the required shielding will vary. However, since the differences between the white beam transport (see 8.3) and the monochromatic beam transport (see 8.1) are quite small for the vacuum loss scenario, one may consider adopting the white beam transport shielding recommendations for a pink beam transport. This will be a safe and conservative solution. Otherwise, individual pink beam transport calculations shall be required.

8.3 White beam transport

White beam transport carries both the synchrotron beam and the primary gas bremsstrahlung. The white beam transport guideline is only calculated for air scattering due to the loss of vacuum. Solid scattering of primary gas bremsstrahlung (e.g; a diagnostic flag) will require very significant shielding that is not practical for a beam transport pipe. In such a case, a local heavily shielded enclosure may be more appropriate.

<u>Guidelines and assumptions</u>

- There shall be no solid scatterers in the white beam transport line.

- The white beam is ≥ 25 mm from the inside wall of the pipe.

- Ray traces shall demonstrate that no synchrotron or bremsstrahlung rays can hit the transport pipe.

- For an ID beamline, the shielding for the white beam transport pipe shall be at least 7 mm Pb.

- For a BM/3PW beamline, the shielding for the white beam transport pipe shall be at least 5 mm Pb.

Basis: Appendix 8.3

8.4 Transport pipe – shielded enclosure penetrations

A typical transport pipe penetration for a shielded enclosure consists of a 'guillotine'. In some cases, there may be small line-of-sight holes between the guillotine and the transport pipe due to small surface mis-matches between the transport pipe and the guillotine. One way to address this is to add a tight-fitting lead collar around the transport pipe, immediately outside of the shielded enclosure penetration. The role of the collar is to increase the Pb-to-transport pipe contact along the transport pipe. The added contact length (length of the collar) reduces the amount of radiation that can come through small holes. The ratio of the contact length to the size of the holes should be > 10X.

9. GUIDELINES FOR MANAGING SECONDARY BREMSSTRAHLUNG

Simulations show that significant amount of secondary (scattered) bremsstrahlung is created when the primary gas bremsstrahlung is incident on substantial white beam components. These white beam components primarily disperses the primary bremsstrahlung without significant energy loss; thereby greatly increasing the angular extent of very high-energy bremsstrahlung photons. Simulations show that it is necessary to intercept this secondary bremsstrahlung *before* they hit the downstream white beam enclosure panel. In this section, secondary bremsstrahlung from two common white beam components, namely the copper or Glidcop fixed masks/white beam stops/white beam slits and white beam optics are considered. Beamlines that have components other than silicon optics and copper masks/stops/slits in the primary bremsstrahlung path may require further study. Thin diamond screens or thin silicon cystals are not expected to be a significant source of secondary bremsstrahlung. The key to managing secondary bremsstrahlung is to place shielding as close to the scattering source as possible.

Two approaches for managing secondary bremsstrahlung are presented: (1) the use of supplementary shielding and (2) the use of an exclusion area.

9.1 Supplementary shielding against secondary bremsstrahlung

A secondary bremsstrahlung ray-trace from the white beam components to the white beam enclosure downstream panel is useful to properly design the supplementary shielding. Particular care should be given to the white beam enclosure downstream panel penetration. It should be noted that monochromatic beam photon shutters (see 6.4) may not provide sufficient shielding against the low-angle secondary bremsstrahlung.

<u>Guidelines and assumptions</u>

- The white beam/bremsstrahlung scatterer is located inside a white beam enclosure as described in Section 7.
- There is a primary bremsstrahlung stop in the white beam enclosure.
- The recommended thickness of Pb secondary shielding is given in Table 9-1.
- If W is used, the thickness is 2/3 that of Pb.
- The distance between the edge of the shielding and extremal secondary bremsstrahlung rays should be at least 3 mm.
- If non-contiguous pieces shielding are used, the overlap between them should be at least 3 mm.
- All secondary bremsstrahlung shielding inside the white beam enclosure shall be located at least 1 m upstream from the enclosure downstream panel.
- It is strongly recommended that bremsstrahlung collimators or shielding be placed as close as possible downstream of all primary bremsstrahlung scatterers.
- It is generally useful to extend the lateral dimensions of the primary bremsstrahlung collimators and stops beyond the 3 Moliere radius requirement stated in section 6.1 and 6.2 in order to capture the low-angle secondary bremsstrahlung scatter.

Table 9-1: Recommended secondary bremsstrahlung shielding for a variety of scatterers

Scattering angle/Scatterer	> 8 deg	4 to 8 deg	2 to 4 deg	< 2 deg
1 m long Si mirror	-	5 cm Pb	7 cm Pb	9 cm Pb
0.1 m long Si	-	-	5 cm Pb	7 cm Pb

monochromator				
Copper		5 cm Pb	7 cm Pb	9 cm Pb

Note: Scattering angle is measured off the incident white beam.

Basis: Appendix 9.1

9.2 Use of an exclusion area to mitigate secondary bremsstrahlung

In cases where it is not possible to install sufficient supplementary bremsstrahlung shielding within the white beam enclosure, an exclusion area immediately downstream of the white beam enclosure may be considered, subject to approval by the NSLS-II management. Per ALARA, it is strongly recommended that at least some supplementary bremsstrahlung shielding be placed inside the white beam enclosure in order to reduce the dose rates behind the white beam enclosure, even if that space is an exclusion area. The use of exclusion areas is generally discouraged.

The following guidelines are for the case where no supplementary shielding at all is installed and the scatterer is a 1 m long silicon mirror. Given the similarities in supplementary shielding required between a copper scatterer and a 1 m Si mirror, these guidelines should apply to the white beam components considered in this section, namely, the white beam silicon optics and copper (Glidcop) masks and stops.

<u>Guidelines and assumptions</u>

- Access into the exclusion area shall be controlled. The level of control and how it is implemented depends on the dose rates and is subject to NSLS-II management approval.

- For an ID beamline, the exclusion area needs to extend at least 7 m downstream of the white beam enclosure, and at least 1.3 m laterally from the white beam center line.

- For a BM/3PW beamline, the exclusion area needs to extend at least 3.5 m downstream of the white beam enclosure, and at least 1 m laterally from the white beam center line.

Basis: Appendix 9.2

10. References

1. "Guidelines for NSLS-II Beamlines and Front End Radiation Shielding Design", P.K. Job and W. R. Casey. LT-ESHDES-08-003

2. "Revised Guidelines for the NSLS-II Beamline Shielding Design", P.K. Job and Robert Lee. LT-C-ESH-STD-001
3. "Insertion Device Front End Ray Tracing Procedure", L. Doom. PS-C-ASD-PRC-147
4. " Beamline Synchrotron and Bremsstrahlung Ray Tracing Procedure", M. Carlucci-Dayton. PS-C-XFD-PRC-008
5. "Photon Sciences Shielding Policy", E. Johnson, R. Lee and M. Bebon. PS-C-ASD-POL-005.
6. "Attenuation of Scattered Monochromatic Synchrotron Radiation in Iron and Lead", Z. Xia and W.-K. Lee. NSLS-II TN145.

11. Appendices

Appendix A: Gas Bremsstrahlung FLUKA Source Definition

To limit the total computation time required by the FLUKA transport of gas bremsstrahlung (GB), the models did not simulate the discrete generation of bremsstrahlung photons in low pressure gasses, but instead used a custom GB generator based on an analytic representation of the source's energy spectrum which was scaled in intensity in accordance with the experimental estimates of total GB power [LT-C-ESH-STD-002]. This custom source assumes a 1/E energy spectrum dependency, with a maximum energy of 3GeV, and generates internally the corresponding probability density function from analytical descriptions. The resulting forward photon spectrum was compared with the output of a separate simulation that models the discrete interaction of a 3GeV electron beam with a column of air at normal pressure. As seen below, up to a scaling factor the forward photon energy spectrum of the custom source is very similar to the result of the discrete simulation.

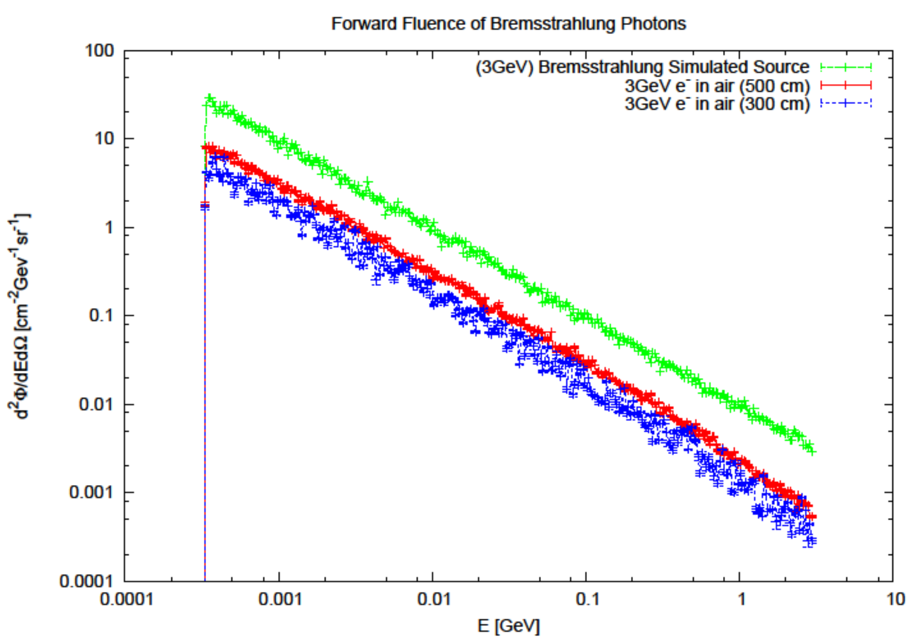


Figure A1: Comparison of gas bremsstrahlung photon sources – energy spectrum of photons generated via discrete gas interactions versus spectrum generated from analytic probability distribution function.

Appendix B: FLUKA Estimators and Scoring

Using the specified beam and geometry, the FLUKA Monte Carlo calculations produce estimates of the ambient dose equivalent rates by scoring particle track density (of all particles or using only selected particle species) over a 3d grid encompassing the volume of interest. To form a general idea of the radiation field inside the enclosure we choose two ~10cm thick “slices”, one vertical (marked “Vertical”) and another horizontal (marked “Midplane”), both including the beam axis, and average the dose rates across the thickness of the slice in order to create 2d projections along the corresponding sections.

To assess the dose rates in *close proximity* to enclosure walls, where the rates will be highest, from the full 3d dose rate distributions we selected and averaged over a 2cm thick layer placed in the immediate proximity (at 2mm distance) of the exterior surfaces of the downstream wall, the lateral wall and the roof of the FOE. Due to the symmetry of the geometry, the maxima of the lateral wall dose distribution are located at the intersection with the horizontal beam plane, while for the roof dose distribution the maxima are located at the intersection with the vertical/longitudinal beam plane. In order to capture and quantify the values of these maxima, the 1d dose rate plots presented in various cases have taken 1cm wide slices through the corresponding 2d wall dose distributions described before, along the directions created by these intersecting planes. The downstream wall dose rate projections were sliced horizontally (1cm wide slice) at a height corresponding to the center of the wall aperture.

Appendix 6.2: Basis for minimum offset distance for aperture in an integral stop-mono-aperture device

Source

The beam used the gas bremsstrahlung source described in Appendix A, normalized at 17µW and 7.2µW incident power, for long and short straight cases, respectively. The two values correspond to the estimated bremsstrahlung power generated by a 500mA electron beam of 3GeV, assuming that the vacuum in the straight sections is better than 10^{-9}Torr.

Geometry

The study used a simplified rectangular white beam enclosure, 10m long, terminated by a 5cm thick Pb downstream wall equipped with mono beam aperture of 6inch diameter (figure A6.2-1). An integral mono aperture and bremsstrahlung stop (30x30x30 cm cube) was placed 35cm away from the downstream wall and contained a 2x1cm rectangular aperture (figures A6.2-2 and A6.2-3). The primary bremsstrahlung beam, confined to a 6mm radius spot at the aperture location, was translated vertically such that the distance “d” between the edge of the beam cone and the edge of the aperture varied from 1mm to 15mm (figure A6.2-4). The calculations focused on the effects of the aperture offset distance “d” on the dose distribution on the exterior side of the downstream wall.

Four configurations have been analyzed: two values of incident bremsstrahlung power corresponding to long (15.5m) and short (6.6m) straights, and two materials for the bremsstrahlung stop/beam aperture -- lead and tungsten. For the geometries using tungsten bremsstrahlung stops, the length of the device was reduced from 30cm to 20cm, while keeping the same transversal dimensions.

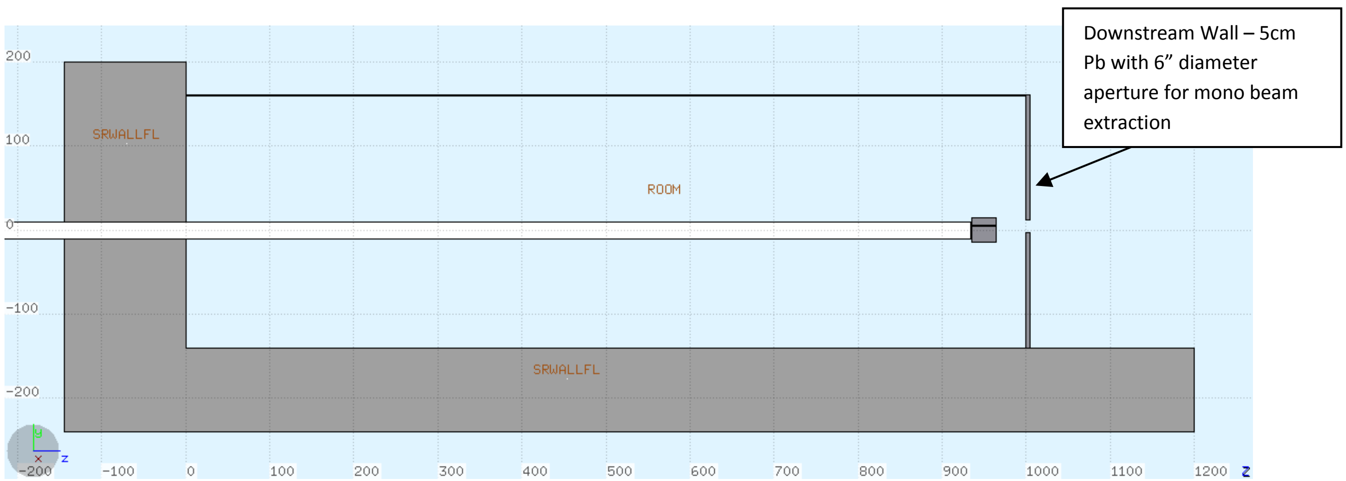


Figure A6.2-1: Vertical section of the white beam enclosure.

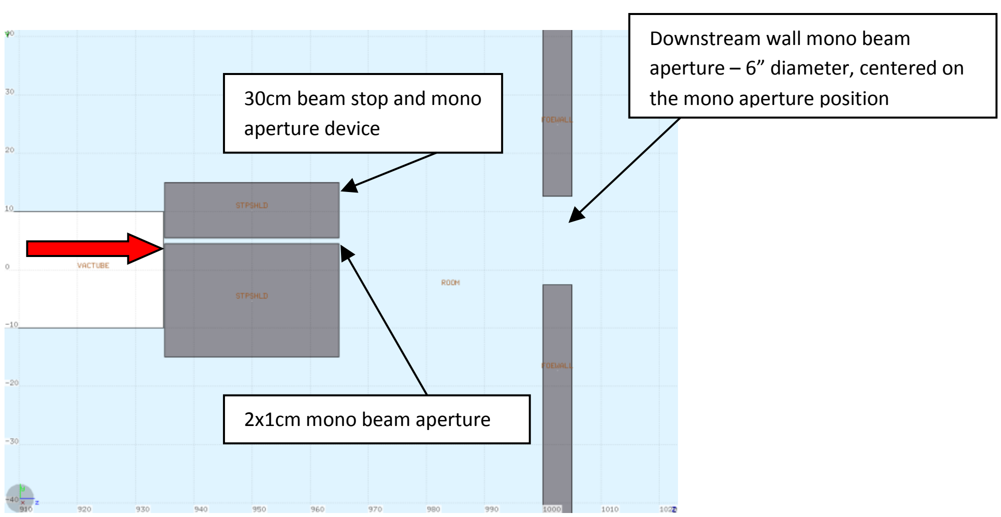


Figure A6.2-2: Vertical section (close-up) of the mono aperture/bremsstrahlung stop and downstream wall.

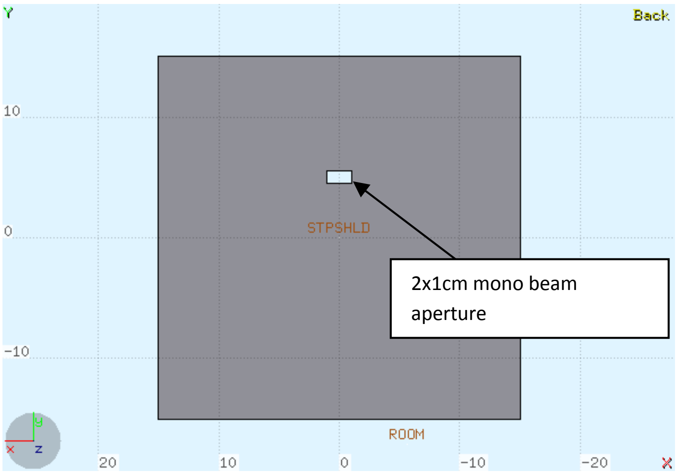


Figure A6.2-3: Transversal section of the mono aperture/bremsstrahlung stop device

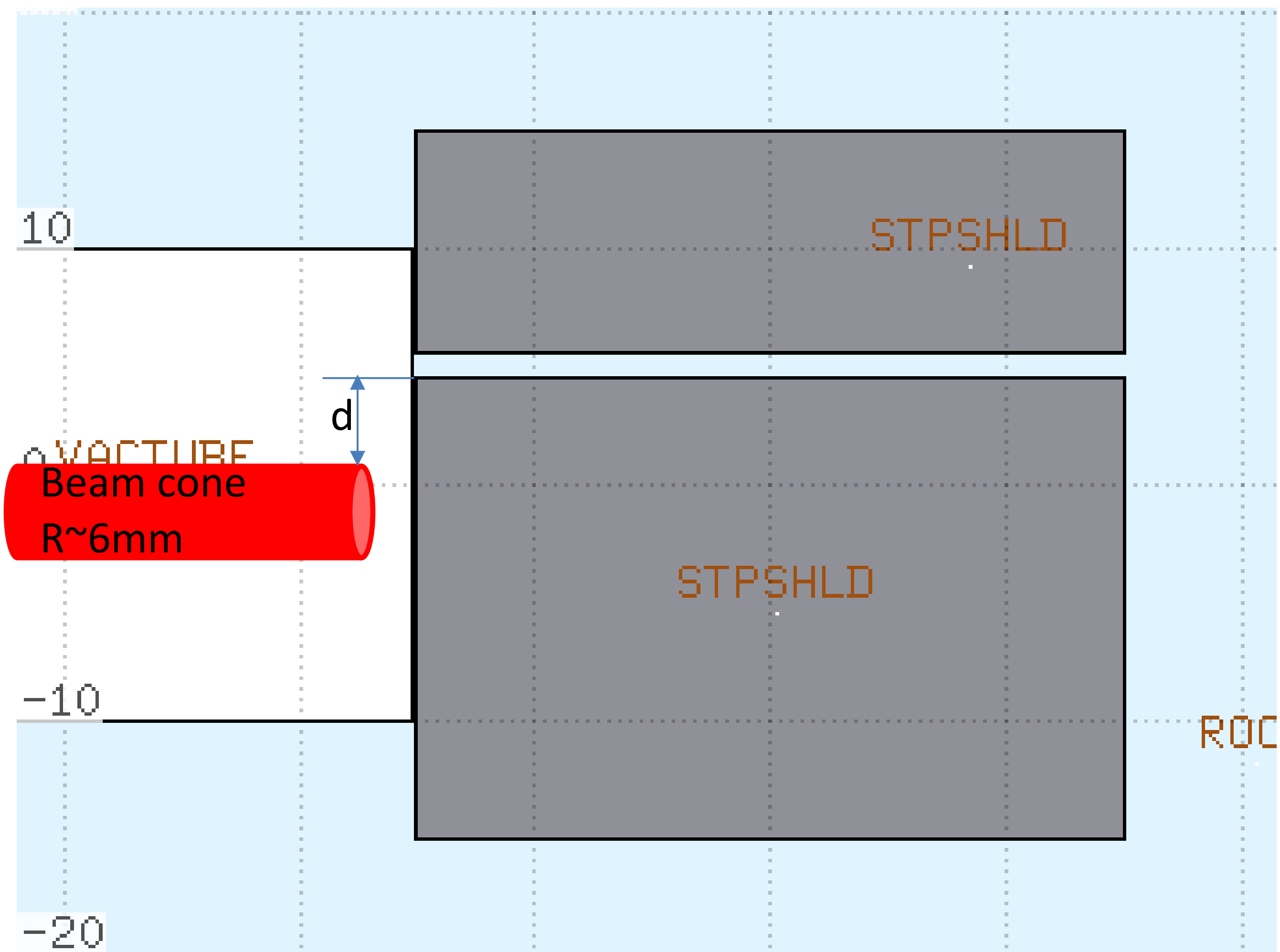


Figure A6.2-4: Positioning of the incident beam relative to the bremsstrahlung stop aperture and the definition of the aperture offset distance "d"

Results & Conclusions

The simulations estimated the ambient dose equivalent rate in contact with the exterior of the downstream wall of the white beam enclosure, when the offset “d” (figure A6.2-4) between the edge of the beam cone and the edge of the mono aperture was varied between 1mm and 15mm, attempting to determine the value beyond which increasing this offset would not yield a reduction of the surface dose rate. The following plots summarize the wall surface contact dose rate along a 1cm wide vertical slice (x=±0.5cm) that includes the projections of the beam and mono aperture axes, for several values of the aperture-beam offset. Four cases, corresponding to two bremsstrahlung stop materials and two incident beam power were analyzed (figures A6.2-5 to A6.2-8).

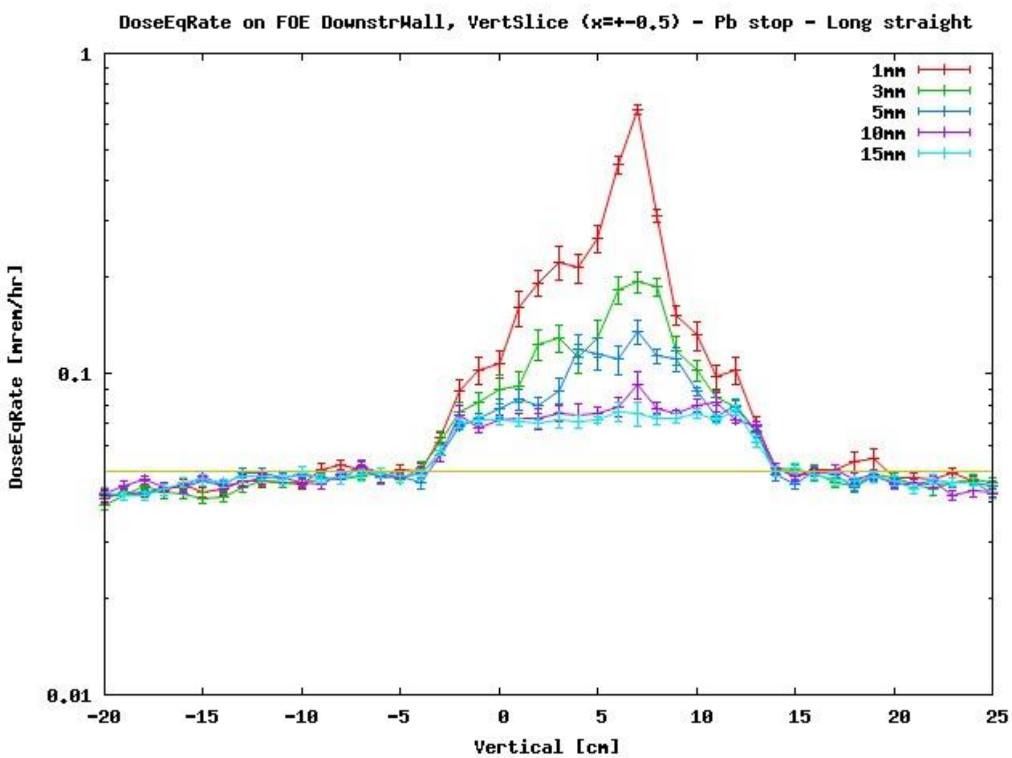


Figure A6.2-5: Vertical slice through the FOE downstream wall surface dose rate at x=±0.5cm for various beam-aperture offset values. Long straight section. Lead bremsstrahlung stop.

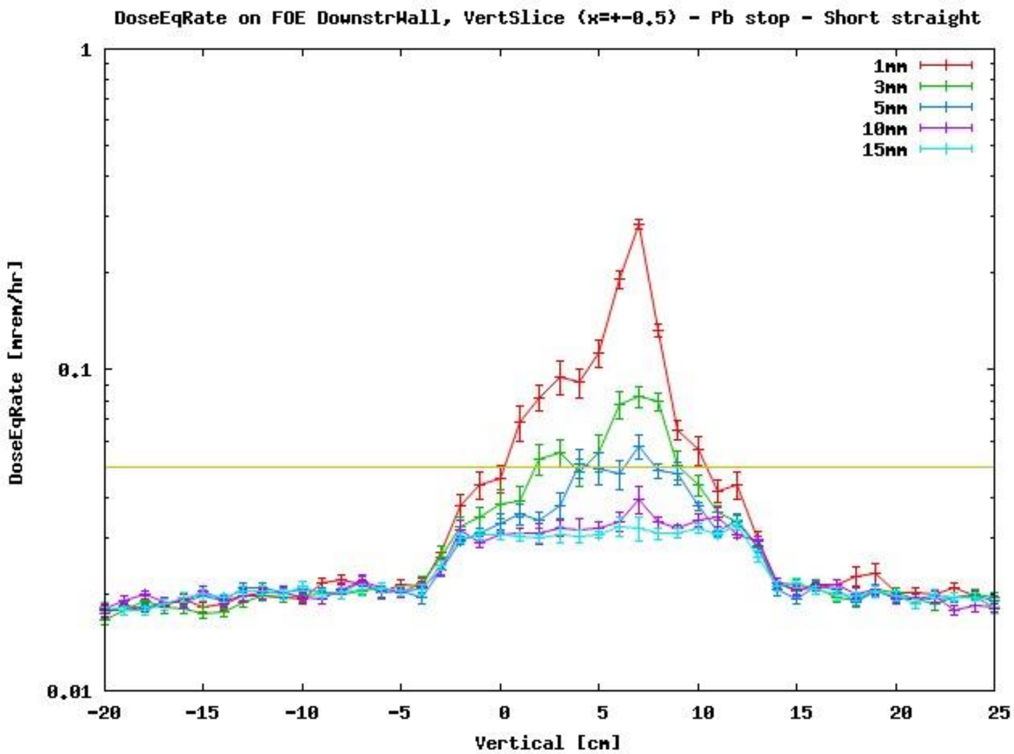


Figure A6.2-6: Vertical slice through the FOE downstream wall surface dose rate at x=±0.5cm for various beam-aperture offset values. Short straight section. Lead bremsstrahlung stop.

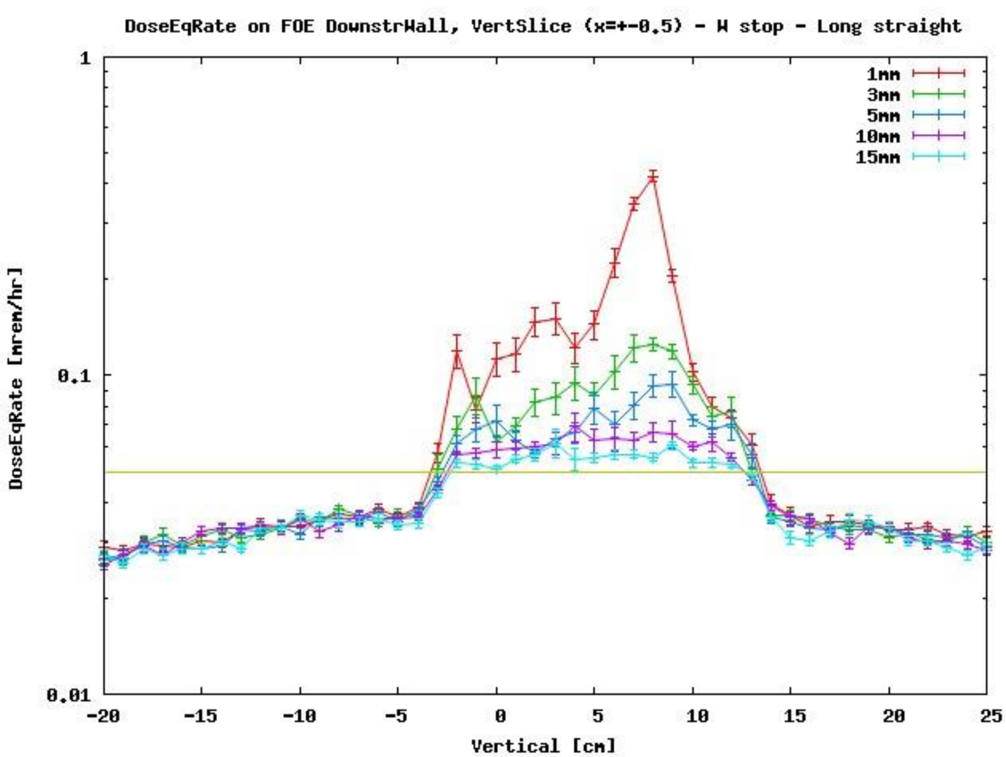


Figure A6.2-7: Vertical slice through the FOE downstream wall surface dose rate at x=±0.5cm for various beam-aperture offset values. Long straight section. Tungsten bremsstrahlung stop.

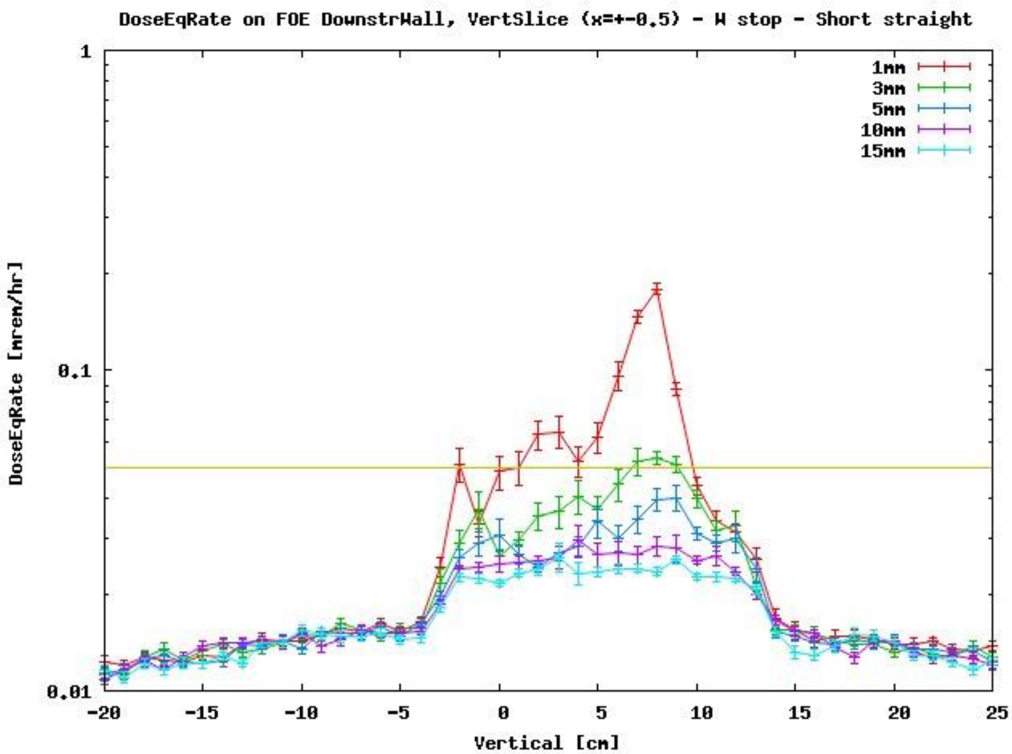


Figure A6.2-8: Vertical slice through the FOE downstream wall surface dose rate at x=±0.5cm for various beam-aperture offset values. Short straight section. Tungsten bremsstrahlung stop.

For all analyzed cases, the contact dose equivalent rate shows little to no reduction when the beam-aperture offset is increased past 10mm. Therefore, in order to keep the dose rates *as low as reasonably achievable* the integral mono aperture bremsstrahlung stop utilized inside white beam enclosures should maintain at least 10mm offset between the edge of the aperture and the edge of the primary bremsstrahlung beam spot.

Appendix 6.4: Basis for monochromatic shutter/stop

The required monochromatic shutter/stop thickness is calculated by STAC8 code. The electron beam energy and current are 3 GeV and 500 mA in the calculation.

Source

The calculation was performed for 22 keV, 66 keV, 87.5 keV, 110 keV and 154 keV photons with 0.1% bandwidth for DW 100, EPU 45, IVU 20, BM and 3PW sources. The source parameters are listed in Table A6.4-1.

Table A6.4-1: NSLS-II Source Parameters

Source	Period (mm)	Length (m)	Beff (T)	No. of periods	Max. source opening	Total power (kW)
DW100	100	7	1.8	70	6 mradH	63.1
IVU20	20	3	1.03	148	1 mradH	13.9
EPU45 (L-mode)	45	4	1.03	89	1 mradH	9.4
BM	-	2.6	0.4	1	10 mradH	0.345
3PW	-	0.25	1.12	1	4 mradH	0.37

Geometry and approach

Shutter is 20 m downstream, perpendicularly to the synchrotron radiation. The dose is calculated directly downstream of the shutter by “NICK” command in STAC 8.

Results and conclusions

The monochromatic shutter/stop thickness is listed in Table A6.4-2 for different sources. The dose rate is <0.05 mrem/h downstream of the shutters.

Table A6.4-2: Shielding recommendations for monochromatic beam shutters and stops

	DW100	EPU45	IVU20	3PW	BM
W	8 mm	5 mm	5 mm	4 mm	1 mm
Pb	20 mm	14 mm	14 mm	12 mm	1 mm

Appendix 7.1a: Basis for ID shielded enclosures

Section 1: Copper scatterer
Source

The 3GeV maximum energy primary bremsstrahlung beam (Appendix A) is confined to ~9mm diameter disk at the target location and was scaled to 17µW total power that corresponds to a 15.5m straight source at 10^{-9}torr.

Geometry

The study used a simplified rectangular enclosure, 10m long, terminated by a 5cm thick Pb downstream wall equipped with a mono beam aperture of 6inch diameter (figure A7.1a-1). Around the aperture, the downstream wall is reinforced by a 5cm thick Pb guillotine, of $1x1m^2$ surface, placed symmetrically around the beam axis. The lateral wall is located 1.0m from the beam axis and is constructed of 18mm Pb. The roof of the enclosure is 3m high, or 1.6m above the beam plane and is made of 6mm Pb. An integral mono aperture and bremsstrahlung stop (30x30x30 cm cube) was placed 35cm away from the downstream wall and contained a 4x2.5cm rectangular aperture. Also, a photon shutter (modeled per LT-C-XFD-SPC-PSH-001) was placed between the bremsstrahlung stop and the guillotine, and configured as in the open position.

The target consists of a Cu cylinder of 3cm diameter located 50cm from the ratchet wall and centered on the beam axis. The length of the cylindrical target was varied between 1cm and 15cm.

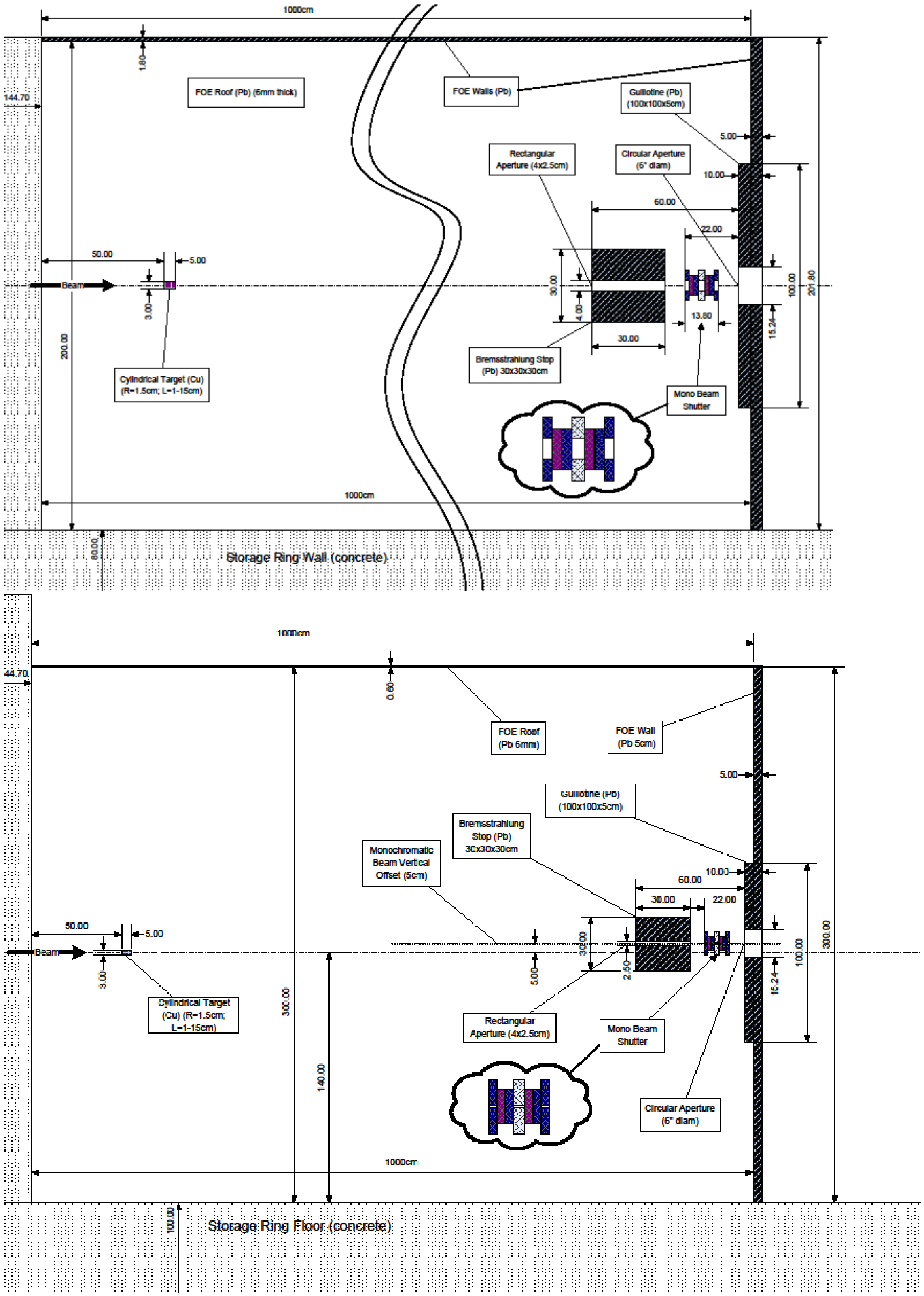


Figure A7.1a-1: FLUKA geometry for ID white beam enclosure. Plan view (top) and side view (bottom)

Results & Conclusions

The FLUKA calculations produced estimates of the ambient dose equivalent rates, from all particle species, for various target thicknesses between 1cm and 15cm. From the full 3d dose rate distributions we selected and averaged over a 2cm thick layer placed in the immediate proximity (at 2mm distance) of the exterior surfaces of the downstream wall, the lateral wall and the roof of the FOE. Dues to the symmetry of the geometry, the dose field maxima of the lateral wall distributions are located at the intersection with the horizontal beam plane, while for the roof distributions they are located at the intersection with the vertical, longitudinal beam plane. In order to capture and quantify the values of these maxima, the 1d dose rate plots presented in figures A7.1a-2 to A7.1a-4

Figure have taken 1cm wide slices through the corresponding 2d dose distributions along the directions created by these intersecting planes. The downstream wall dose rate projections were sliced horizontally (1cm wide slice) at a height corresponding to the center of the wall aperture (Appendix B).

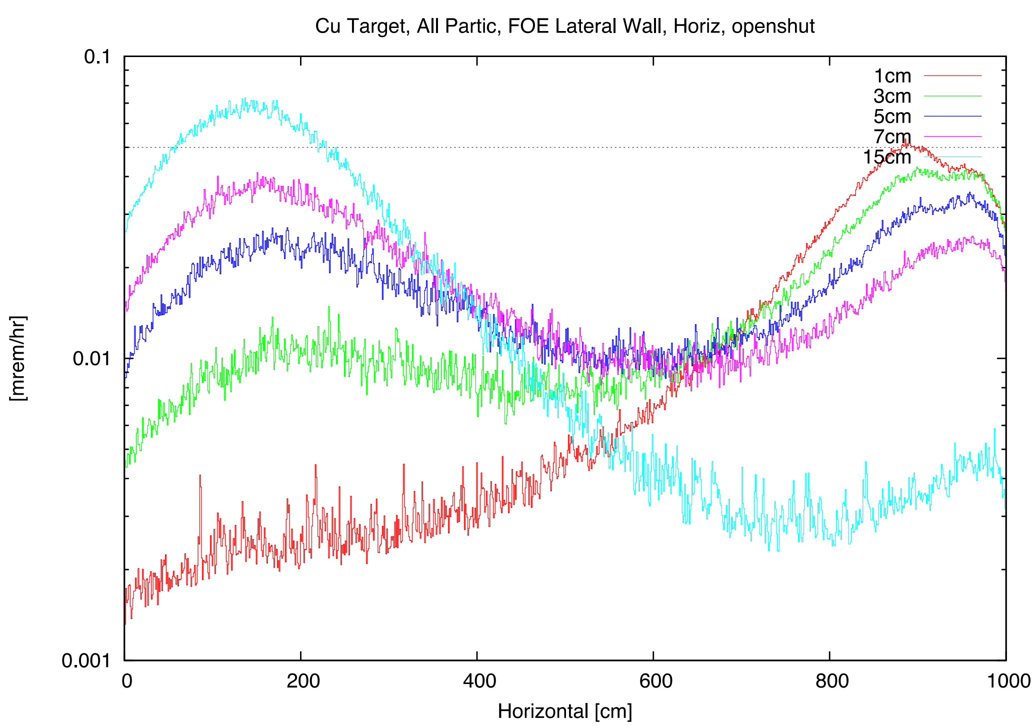


Figure A7.1a-2: Ambient dose equivalent rates on enclosure lateral wall for Cu scatterers of different lengths. Lateral wall is 18 mm Pb.

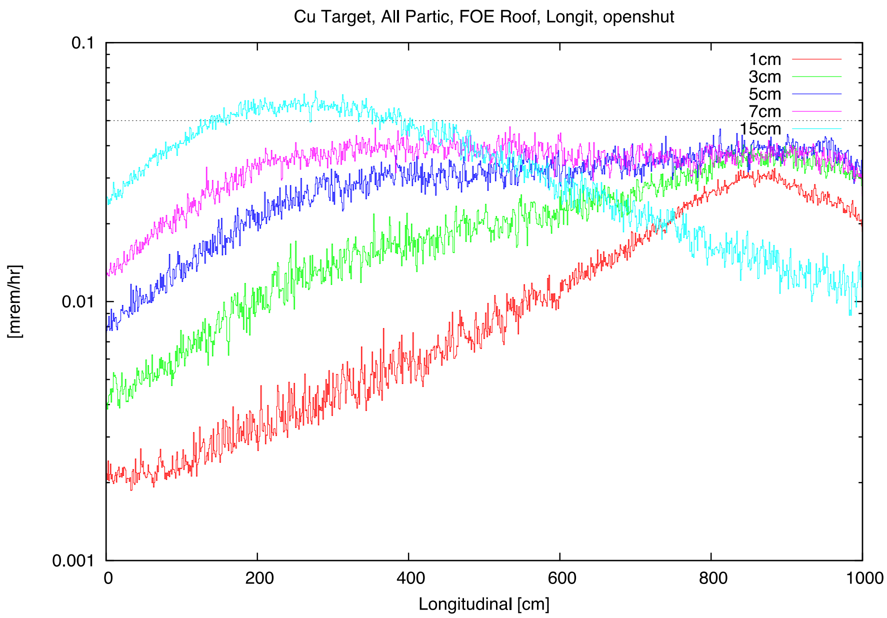


Figure A7.1a-3: Ambient dose equivalent rates on enclosure roof for Cu scatterers of different lengths. Roof is 6 mm Pb.

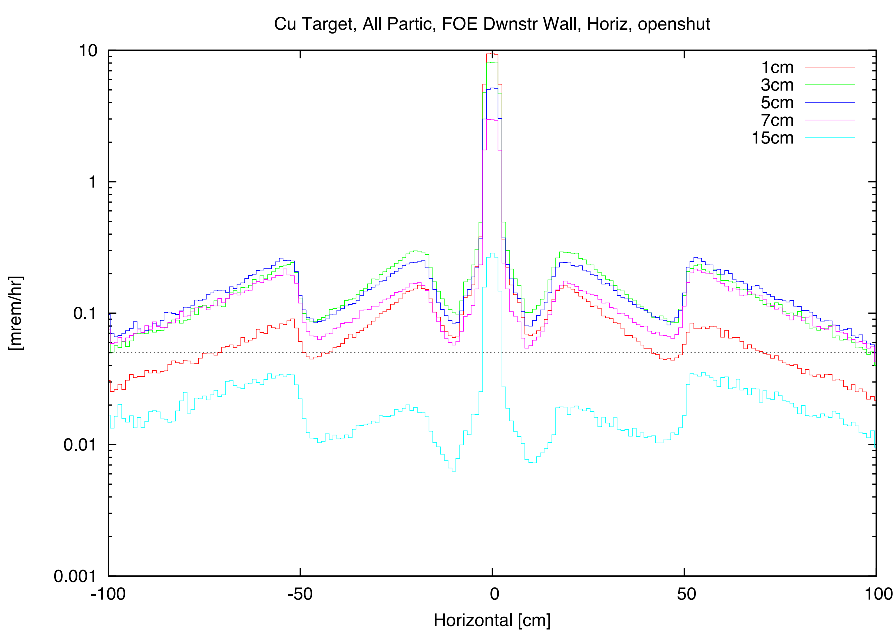


Figure A7.1a-4: Ambient dose equivalent rates on downstream wall for Cu scatterers of different lengths. Downstream wall is 50 mm Pb, with 1 m x 1 m x 5 cm added shielding (see figure A7.1a-1). Central peak is secondary bremsstrahlung coming through the aperture of the integral stop/aperture.

The lateral wall dose peaks at approximately 0.07 mrem/hr when using the 15 cm long scatterer. However, in most NSLS-II ID white beam enclosures, the lateral distance to the wall is 1.2-1.6 m. In the case of 1.2 m distance, distance scaling would reduce the dose to 0.07 x $(1/1.2)^2$ = 0.049 mrem/hr. Furthermore, an egress pathway is located in front of the lateral wall and therefore this is not a normal 100% occupied area. Dose on roof peaks at approx. 0.06 mrem/hr for the 15 cm long scatterer. However, most NSLS-II ID white beam enclosure roofs are 2 m from the beam axis. Here also, the distance scaling would further reduce the dose to 0.06 x $(1.6/2.0)^2$ = 0.014 mrem/hr. In addition, the roof is not a 100% occupied area.

Thus, the recommended white beam enclosure lateral wall shielding of 18 mm Pb and roof shielding of 10 mm Pb is sufficient.

However, calculations clearly show that the downstream wall thickness is not sufficient. Secondary bremsstrahlung created by the copper scatterer is a problem for the downstream wall.

Section 2: Mirror scatterer – configuration I (Pb cube bremsstrahlung stop)

Source

3GeV maximum energy primary bremsstrahlung beam (Appendix A) normalized to 17µW total power that corresponds to a 15.5m straight source at 10^{-9}torr.

Geometry

The study used a simplified rectangular enclosure, 10m long, terminated by a 5cm thick Pb downstream wall equipped with a mono beam aperture of 6inch diameter. Around the aperture, the downstream wall is reinforced by a 5cm thick Pb guillotine, of $1x1m^2$ surface, placed symmetrically around the beam axis. The lateral wall is located 1.0m from the beam axis and is constructed of 18mm Pb. The roof of the enclosure is located 1.6m above the beam plane and is made of 6mm Pb. An integral mono aperture and bremsstrahlung stop (30x30x30 cm cube) was placed 35cm away from the downstream wall and contained a 4x2.5cm rectangular aperture. Also, a photon shutter (modeled per LT-C-XFD-SPC-PSH-001) was placed between the bremsstrahlung stop and the guillotine, and configured as in the open position.

The target consists of a Si mirror 3 cm x 4 cm x 100 cm at 0.25 deg incidence angle. Mirror is located from Z=250 cm to Z=350 cm and reflects the beam upwards.

Results & Conclusions

The dose for the 18 mm Pb lateral wall at 1 m distance and the 6 mm roof at 1.6 m distance slightly exceed target of 0.05 mrem/hr. But guidance calls for 10 mm Pb roof and most stations have more than 1.2 m lateral wall distance and ~ 2.0 m roof distance. In addition, outside lateral wall and the roof are not 100% occupied areas. *Therefore, 18 mm Pb lateral wall and 10 mm Pb roof are reasonable guidelines.*

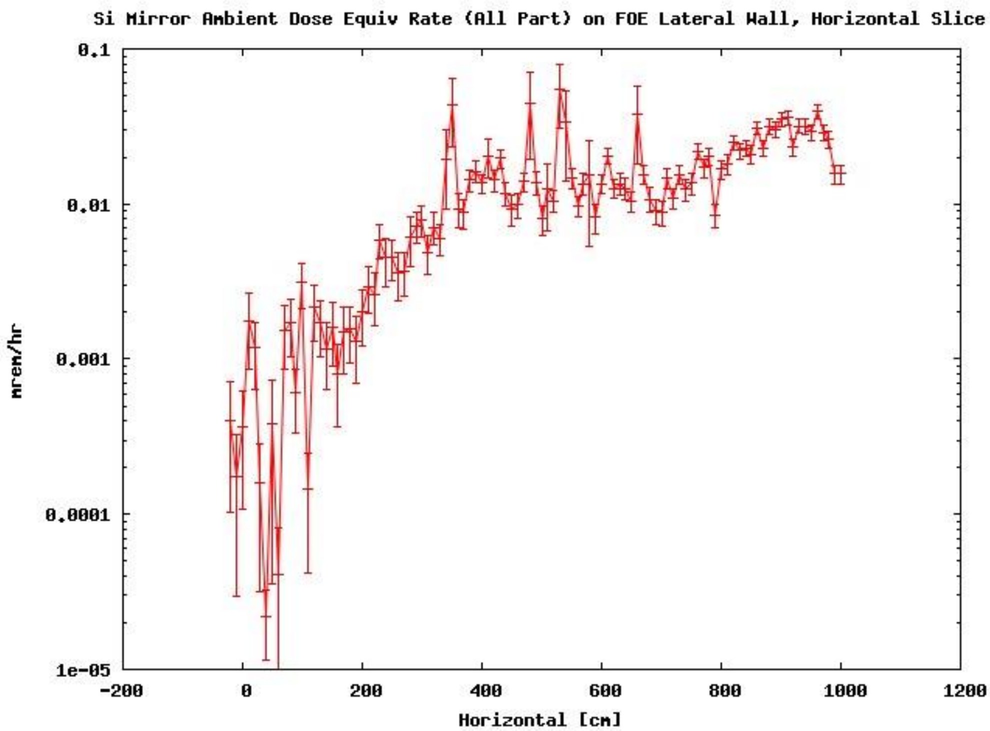


Figure A7.1a-5: Ambient dose equivalent rate on the lateral wall. Lateral wall distance is 1 m from beam.

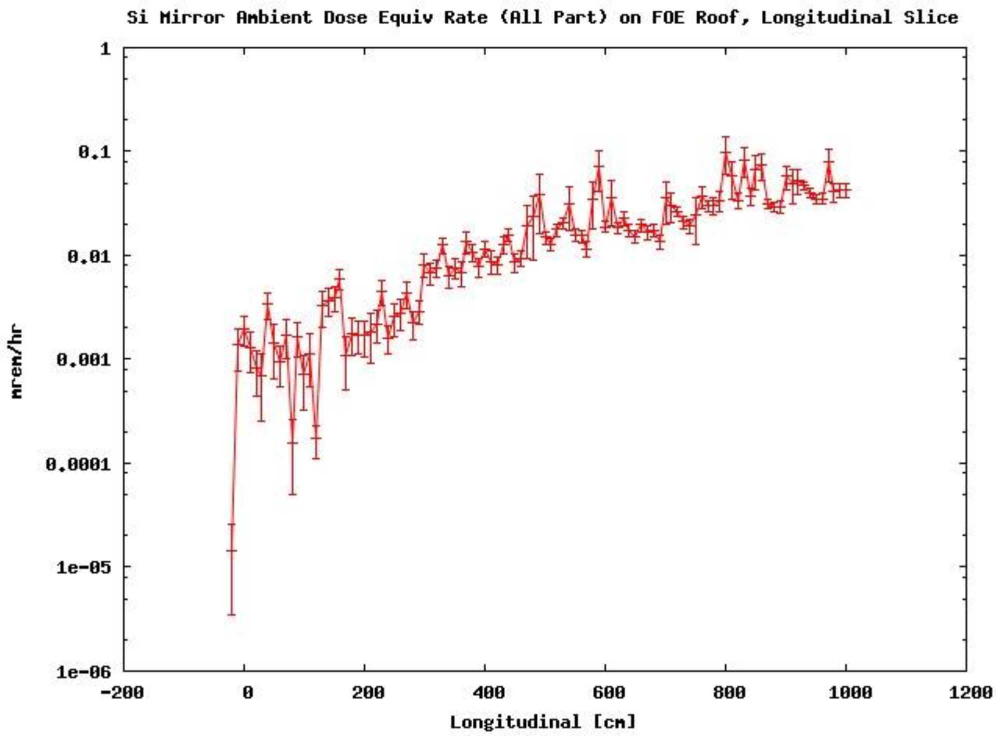


Figure A7.1a-6: Ambient dose equivalent rate on the roof. Roof distance is 1.6 m from beam.

Section 3: Mirror scatterer – configuration II (W cylinder bremsstrahlung stop)

Source

3GeV maximum energy primary bremsstrahlung beam (Appendix A) normalized to 17µW total power that corresponds to a 15.5m straight source at 10^{-9}torr.

Geometry

The study used a simplified rectangular enclosure, 10m long, terminated by a 5cm thick Pb downstream wall without any apertures. The lateral wall is located 1.5m from the beam axis and is constructed of 18mm Pb. The roof of the enclosure is located 2.0m above the beam plane and is made of 6mm Pb (figures A7.1a-7 and A7.1a-8).

The bremsstrahlung stop consists in a 6cm diameter W cylinder, 20cm long, located 3.04m downstream of the Si mirror. A white beam stop was modeled as a Cu cylinder 1.5cm diameter, 3cm long, located 1cm in front of the bremsstrahlung stop.

The target consists of a Si mirror 3 cm x 4 cm x 100 cm at 0.25 deg incidence angle. Mirror located from Z=250 cm to Z=350 cm and reflects the beam upwards.

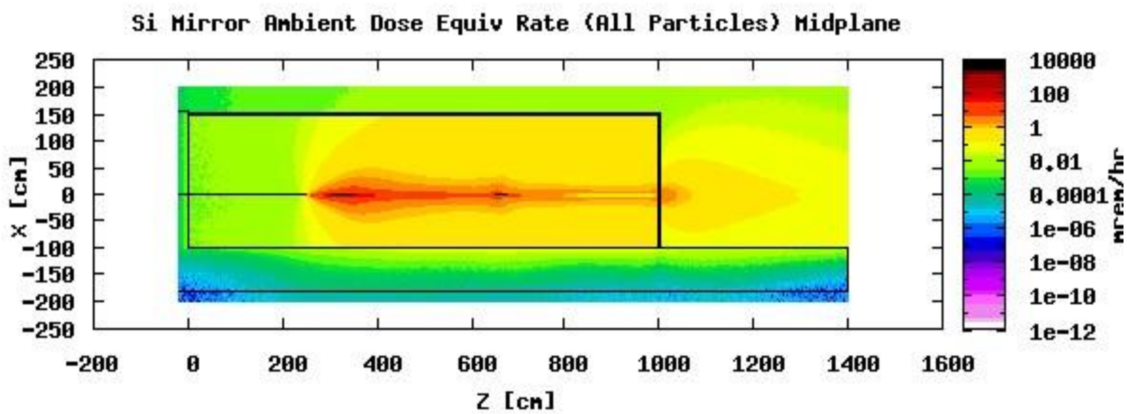


Figure A7.1a-7: Mirror scatterer configuration II (top view). Midplane ambient dose rate distribution.

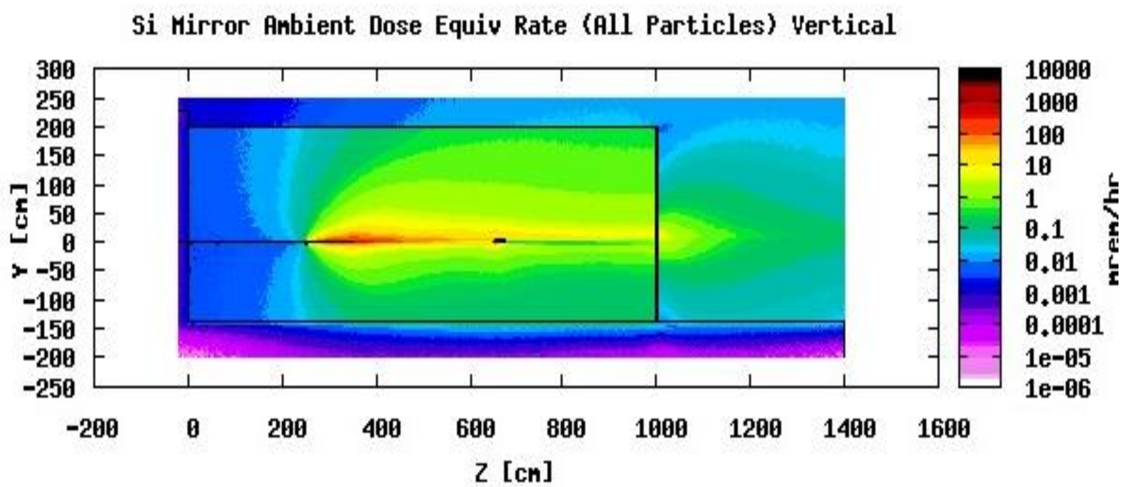


Figure A7.1a-8: Mirror scatterer configuration II (side view). Vertical plane ambient dose rate distribution.

Results & Conclusions

Although the geometry of configuration I and II are slightly different with regards to the primary bremsstrahlung stop and photon shutter, these differences do not significantly affect the lateral wall and roof doses (figures A7.1a-9 and A7.1a-10). In configuration I, where the lateral wall is 1.0 m from the beam, the peak dose is about 0.04 mrem/hr. We would expect that if the lateral wall is 1.5 m away, the dose should be 0.04 x $(1.0/1.5)^2$ = 0.018 mrem/hr. The simulation of configuration II shows (figure A7.1a-9) that for the 1.5 m lateral wall case, the dose is close to 0.018 mrem/hr, confirming the $1/r^2$ relationship. Thus, this shows that *the 18 mm Pb lateral wall is sufficient for a mirror scatterer even at 1.0 m lateral wall distance.*

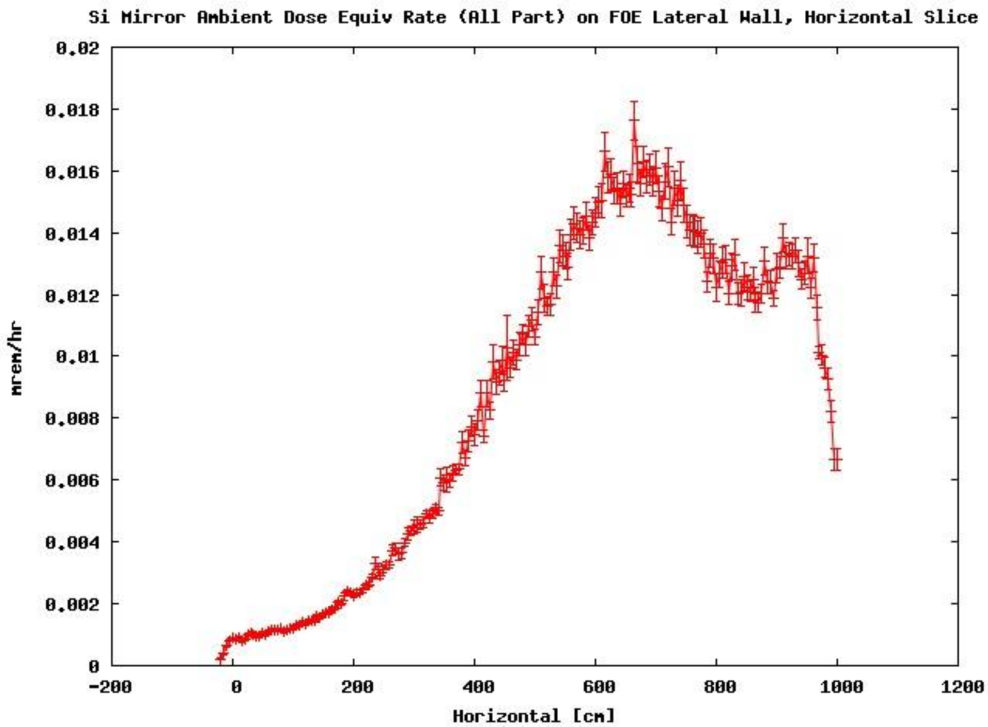


Figure A7.1a-9: Ambient dose equivalent rate on the lateral wall along the midplane. Lateral wall distance is 1.5 m.

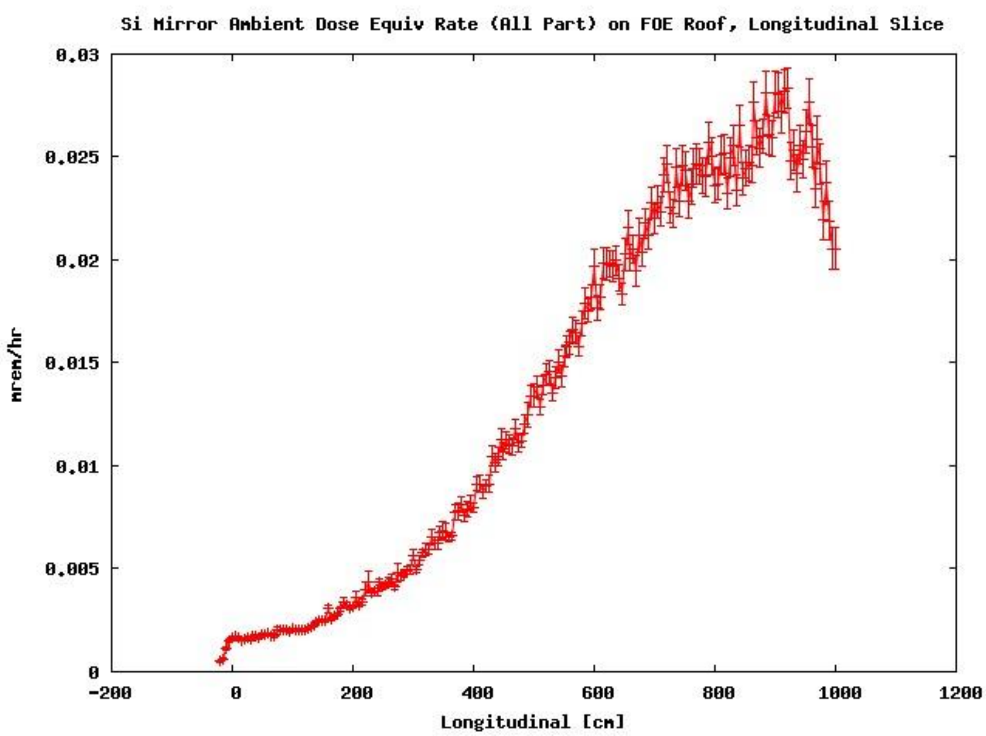


Figure A7.1a-10: Ambient dose equivalent rate on the roof. Distance to roof is 2m.

Appendix 7.1b: Basis for 3PW shielded enclosures

Source

The 3GeV maximum energy primary bremsstrahlung beam (Appendix A) was normalized to 7.2μW total power that corresponds to a 6.6m short straight source at 10^{-9}torr.

Geometry

The 3PW study used a white beam enclosure 10m long, terminated by a 3cm thick Pb downstream wall equipped with mono beam aperture of 6 inch diameter. Around the aperture, the downstream wall is reinforced by a 5cm thick Pb guillotine, of $1x1m^2$ surface, placed symmetrically around the beam axis. The lateral wall is located 0.67m from the beam axis. The calculations used various thicknesses for the lateral wall. The roof of the enclosure is located at 2.1m above the beam plane and is made of 4mm Pb. An integral mono aperture and bremsstrahlung stop (30x30x30 cm cube) was placed 35cm away from the downstream wall and contained a 4x2.5cm rectangular aperture. Also, a photon shutter (modeled per LT-C-XFD-SPC-PSH-001) was placed between the bremsstrahlung stop and the guillotine, and configured as in the open position (figures A7.1b-1 and A7.1b-2).

The target consisted of a 3 cm diameter Cu scatterer, 15 cm long, located 0.5 m from the ratchet wall. Based on previous studies, this configuration creates the most scatter in the vicinity of the copper target.

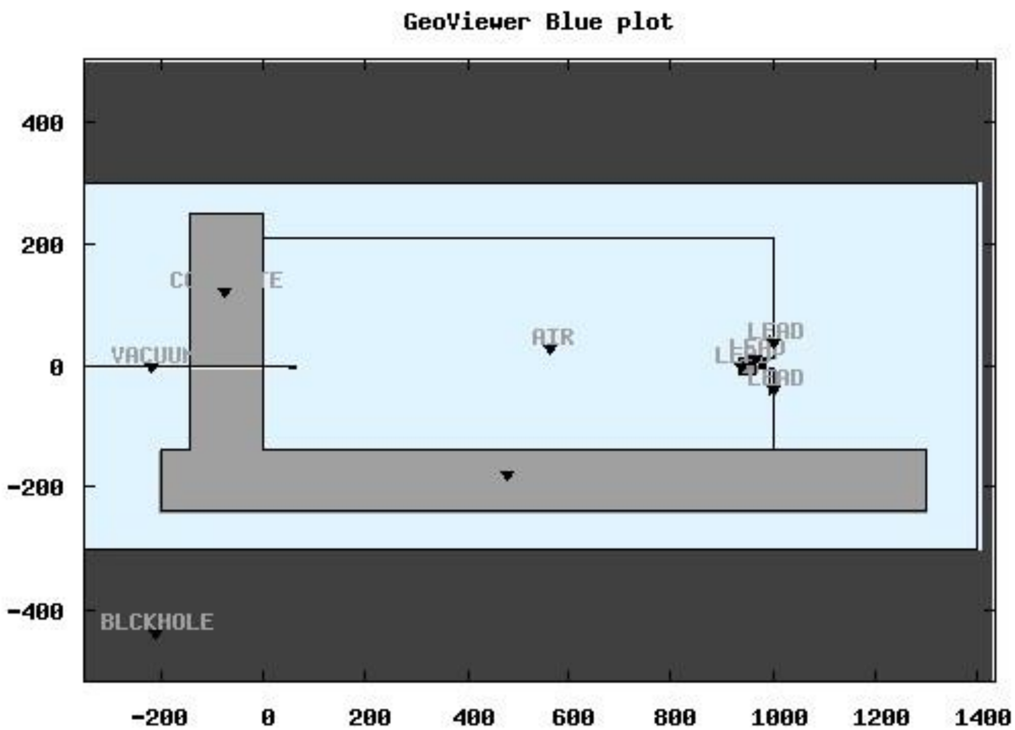


Figure A7.1b-1: FLUKA geometry configuration (side view)

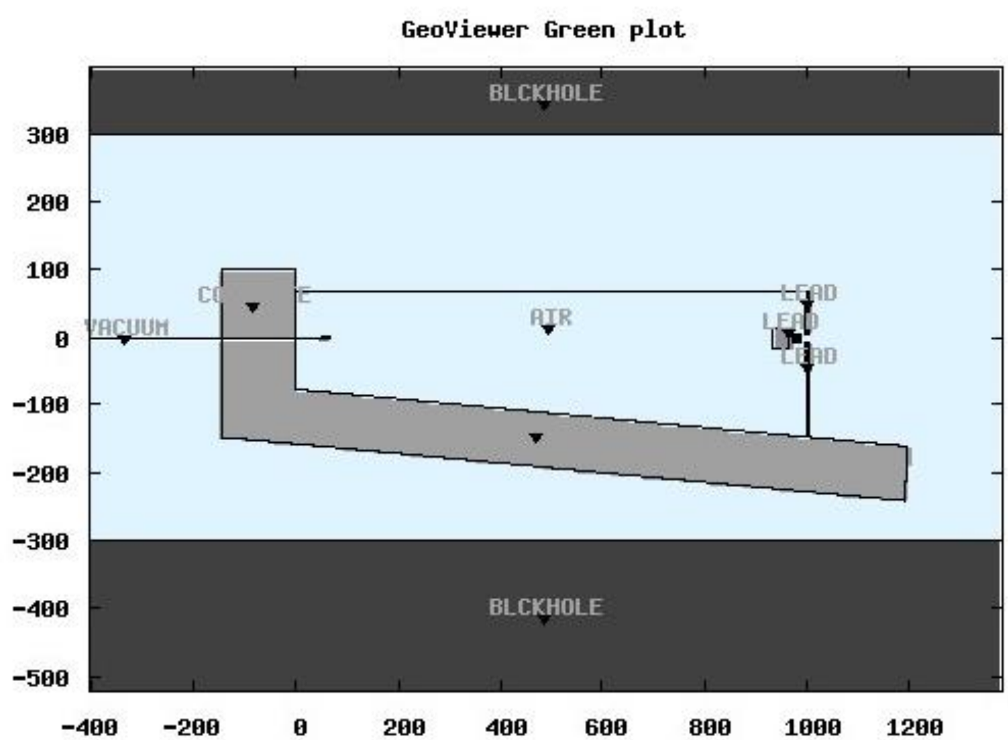


Figure A7.1b-2: FLUKA geometry configuration (top view)

Results & Conclusions

At ~0.018mrem/hr the peak dose rate for roof locations is comfortably within limits and therefore, the 4 mm Pb roof provides sufficient protection for 3PW white beam enclosures (figure A7.1b-3).

Calculations show that 20 mm of Pb is not sufficient to keep the maximum dose rate for the 3PW white beam enclosure lateral wall under 0.05 mrem/hr (figure A7.1b-4). However, it should be noted that there is an egress pathway right next to the white beam enclosure and so, the area immediately outside the white beam enclosure lateral wall is not an occupied area. Based on this, and the desire to have a similar lateral wall thickness as the ID white beam enclosures, *the recommended lateral wall thickness for 3PW white beam enclosures is 18 mm Pb.*

3PW enclosure roof requires less lead than ID enclosures because while at the same distance from the beam, the bremsstrahlung power is lower, at about 42%, as the source has only 6.6 m of straight section compared with 15.5 m for the ID.

3PW lateral wall requires about the same lead thickness (or more) as the ID because the wall is closer to the beam. The distance term $(0.67)^2$ is comparable to the ratio of the straight sections (6.6/15.5). The lateral wall peak dose for the 3PW case is ~0.06 mrem/hr (figure A7.1b-4 -- avg of 15 mm Pb and 20 mm Pb) and for the ID case (see figure A7.1a-2) is 0.07 mrem/hr.

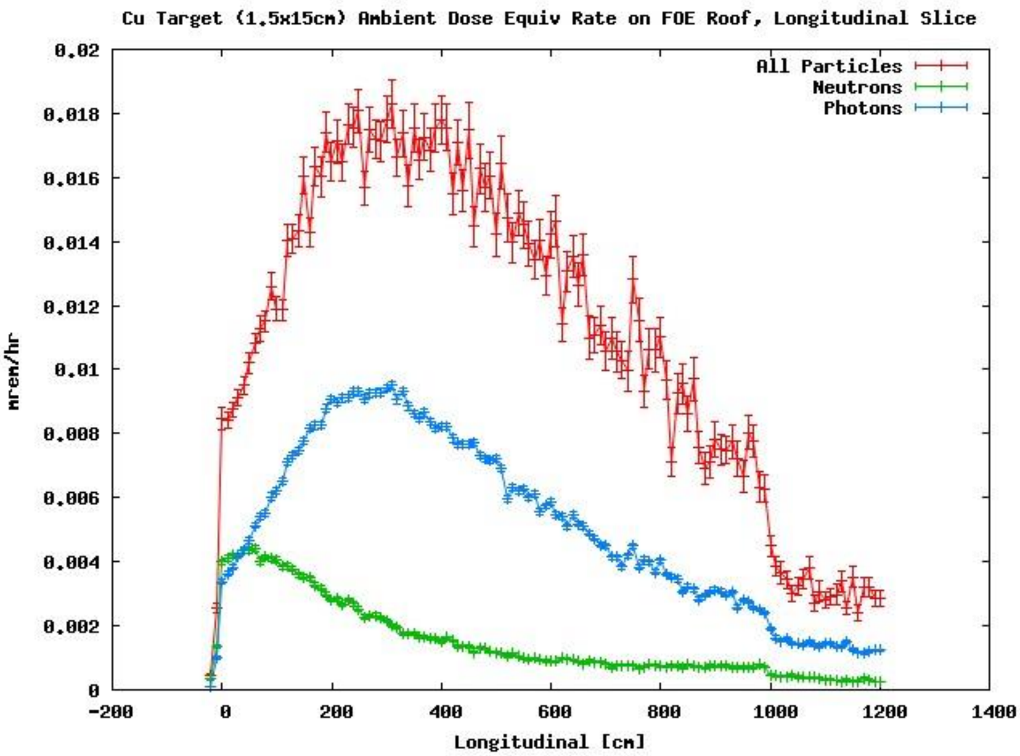


Figure A7.1b-3: Ambient dose equivalent rates on enclosure roof. Roof is 4mm Pb.

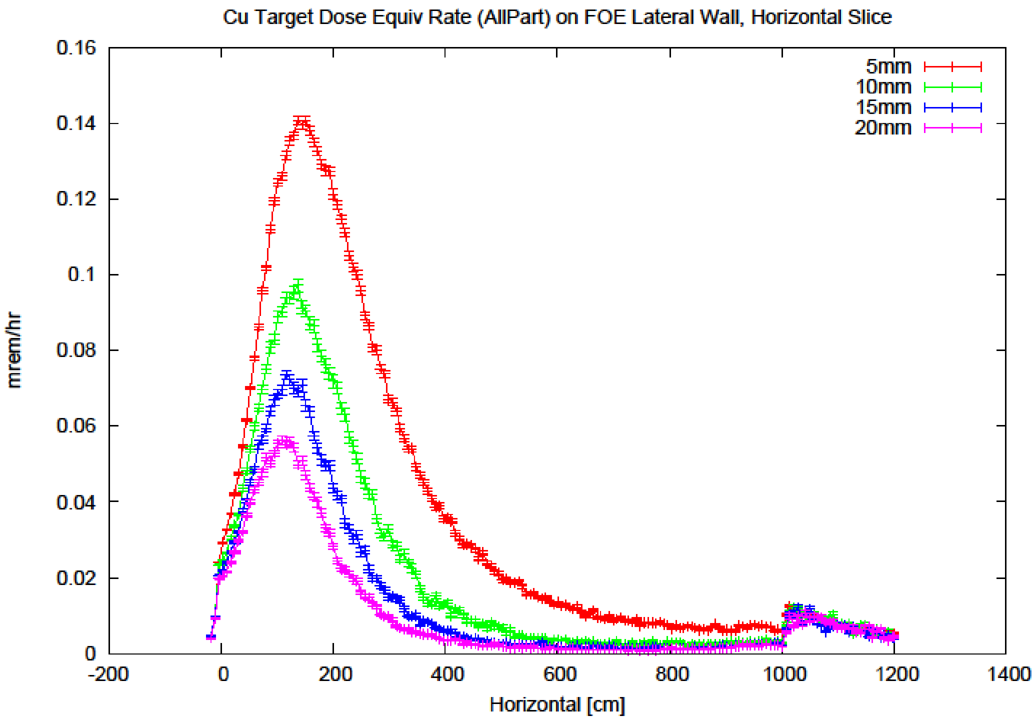


Figure A7.1b-4: Ambient dose equivalent rates on lateral wall function of wall thickness.

Appendix 8.1a: Basis for monochromatic beam transport, solid scatterer

For solid scatterers (Cu or Si), the required monochromatic beam transport pipe thickness is calculated by STAC8. The electron beam energy and current are 3 GeV and 500 mA in the calculation.

Source

The calculation was done for 22 keV, 66 keV, 88 keV, 110 keV and 154 keV photons with 0.1% bandwidth for DW 100, EPU 45, IVU 20, BM and 3PW sources.

The photon flux from DW100 is listed in Table A8.1a-1, EPU45 in Table A8.1a-2, IVU20 in Table A8.1a-3, BM in Table A8.1a-4 and 3PW in Table A8.1a-5.

Table A8.1a-1: Monochromatic Photon Beam Energy and Bandwidth for DW100

Energy (keV)	Bandwidth (keV)	p/ev/sec/mrad/mA	Photons/sec
22	0.022	1.294E11	8.54E+15
66	0.066	1.343E9	2.66E+14
88	0.088	1.573E8	4.15E+13
110	0.11	1.878E7	6.20E+12
154	0.154	2.918E5	1.35E+11

Table A8.1a-2: Monochromatic Photon Beam Energy and Bandwidth for EPU45

Energy (keV)	Bandwidth (keV)	p/sec/mA	Photons/sec
22	0.022	1.604E12	8.02E+14
66	0.066	2.079E9	1.04E+12
88	0.088	7.536E7	3.77E+10
110	0.11	2.172E6	1.09E+09
154	0.154	2.136E3	1.07E+06

Table A8.1a-3: Monochromatic Photon Beam Energy and Bandwidth for IVU20

Energy (keV)	Bandwidth (keV)	p/sec/mA	Photons/sec
22	0.022	7.296E11	3.65E+14
66	0.066	1.536E9	7.68E+11
88	0.088	5.569E7	2.78E+10
110	0.11	1.606E6	8.03E+08
154	0.154	1.579E3	7.90E+05

Table A8.1a-4: Monochromatic Photon Beam Energy and Bandwidth for BM

Energy (keV)	Bandwidth (keV)	p/sec/mA/mrad	Photons/sec

22	0.022	3.17E+07	1.58E+11
66	0.066	5.74E-01	2.87E+03
88	0.088	9.60E-05	4.80E-01
110	0.11	9.55E-09	4.77E-05
154	0.154	1.63E-16	8.16E-13

Table A8.1a-5: Monochromatic Photon Beam Energy and Bandwidth for 3PW

Energy (keV)	Bandwidth (keV)	p/sec/mA	Photons/sec
22	0.022	1.44E+10	2.88E+13
66	0.066	3.25E+07	6.51E+10
88	0.088	1.54E+06	3.08E+09
110	0.11	5.89E+04	1.18E+08
154	0.154	1.00E+02	2.00E+05

Geometry and approach

The solid scatterer is placed perpendicular to the pencil SR beam, and the pipe is a parallel cylinder shielding around the beam. The pipe is with 1” radius and 1 mm stainless steel (SS). Additional required lead thickness is calculated by STAC8 around the pipe.

The solid target used for DW 100 in STAC 8 calculation is a 1.5 cm radius, 1 cm thick cylindrical copper, with its axis perpendicular to SR beam. The solid target used for EPU 45, IVU 20, BM and 3PW is a 1.5 cm radius, 1 cm thick cylindrical Silicon target, with its axis perpendicular to SR beam.

Results and Conclusions

The required Pb thickness for different sources with solid scatterer is listed in Table A8.1a-6.

Table A8.1a-6: Required Lead Thickness to Decrease Dose Rate < 0.05 mrem/h for Solid Scatterer Outside of Pipe, Monochromatic Beam

Source	Required Pb thickness (mm)	Dose rate (mrem/h)
DW100	12	0.04
IVU20	7	0.03
EPU45	7	0.04
BM	n/a	<0.05 with 1 mm SS
3PW	5	0.02

Appendix 8.1b: Basis for monochromatic beam transport, air scatterer

For air scatterers, the required monochromatic beam transport pipe thickness is calculated by FLUKA. The electron beam energy and current are 3 GeV and 500 mA in the calculation.

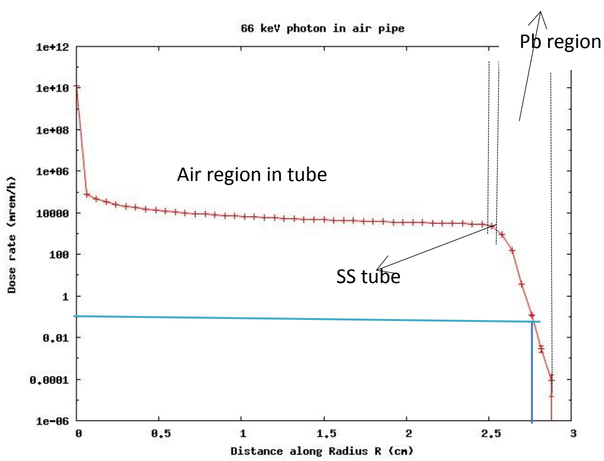
Source

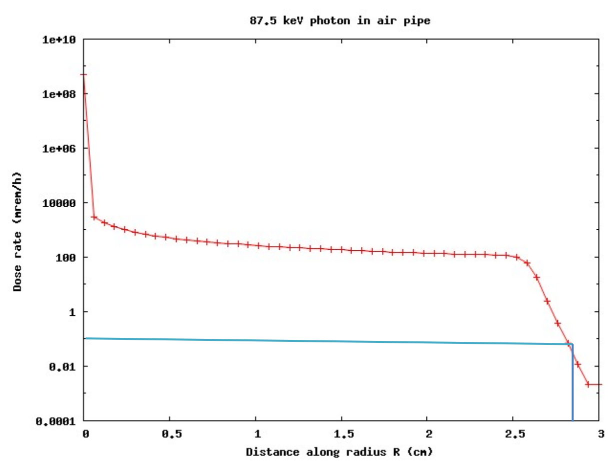
The FLUKA calculation was done for 22 keV, 66 keV, 88 keV, 110 keV and 154 keV with 0.1% bandwidth for DW 100, EPU 45, IVU 20, BM and 3PW sources. The photon energy and flux are the same as shown in 8.1a.

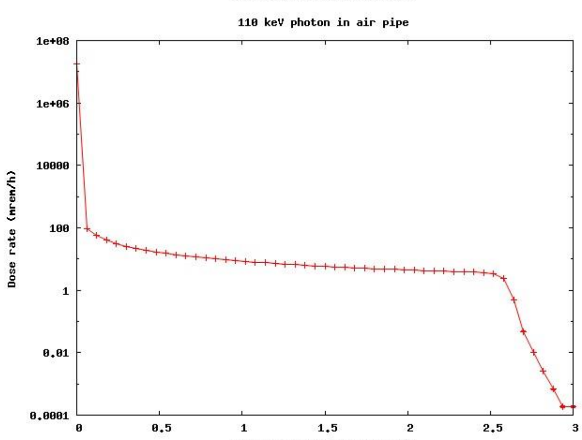
Geometry and approach

In FLUKA model, a 1" radius pipe with 1 mm Stainless Steel (SS) is wrapped by thick PB (~5 mm). The dose rate is tallied along the depth of lead. The pipe is 20 m long filled by 1 atm pressured air. For example: 87.5 keV photons, the required Pb thickness is 2.9 cm – 0.1 cm -2.54 cm = 0.26 cm Pb to decrease dose rate < 0.1 mrem/h.

Results and conclusions







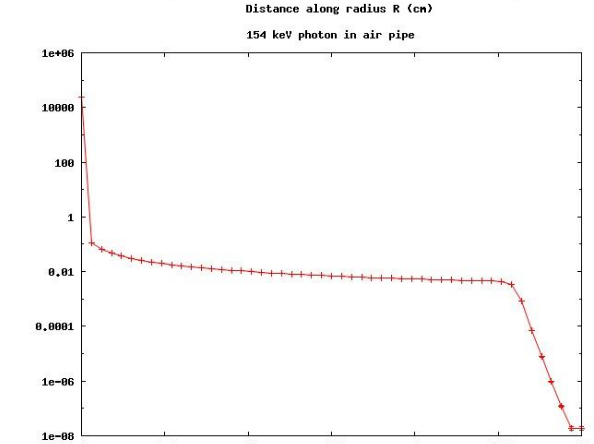


Figure A8.1b-1: Monochromatic beam attenuation in beam pipe for different photon energies (EPU 45 source)

For EPU 45 monochromatic beam, the dose rate outside is dominated by 66 keV and 87.5 keV photons as shown in Figure A8.1b-1. Referring to the above figures, with 3 mm Pb, the dose rate is < 0.5 mrem/h outside of pipe. For other sources, the dose rate can be scaled by flux at different Pb thickness.

Conclusions are summarized in Table 8.1b-1: Recommended shielding for monochromatic beam transport.

Table A8.1b-1: Required Lead Thickness to Decrease Dose Rate < 0.5 mrem/h for Complete Vacuum Loss Outside of Pipe, Monochromatic Beam

Beamline source	Shielding required for < 0.5 mrem/hr due to complete vacuum loss in the beam transport
DW100	5 mm Pb
EPU45	3 mm Pb
IVU20	3 mm Pb
3PW	2 mm Pb
BM	1 mm Fe

Appendix 8.3: Basis for white beam transport guidelines

The shielding requirements for the white beam transport are based on two types of radiation: the synchrotron white beam and the primary bremsstrahlung. Two types of scatterers are considered: air and a copper plate/disk (eg a fluorescent screen).

Section 1: Synchrotron white beam calculations with FLUKA

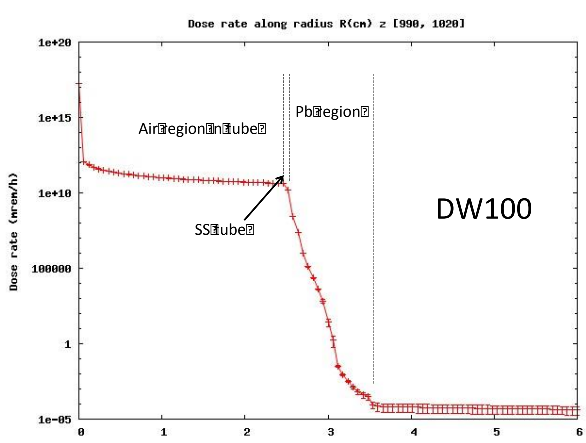
Usually there is no solid scatterer (flags, mono crystals or mirrors) in white beam transport pipe. The required white beam transport pipe thickness is calculated by FLUKA for complete vacuum loss: air scatterer. The electron beam energy and current are 3 GeV and 500 mA in the calculation.

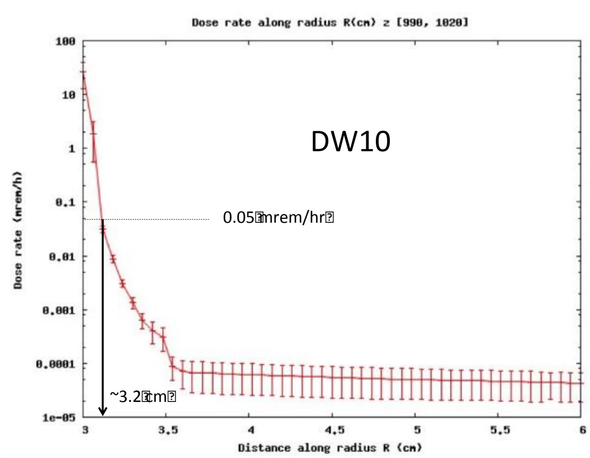
Source

The shielding requirements for the white beam transport are based on two types of radiation: the synchrotron white beam and the primary bremsstrahlung. For air scatterers, the required white beam transport pipe thickness is calculated by FLUKA.

Geometry and approach

In FLUKA model, a 1” radius pipe with 1 mm Stainless Steel (SS) is wrapped by thick PB (~5 mm). The dose rate is tallied along the depth of lead. The pipe is 20 m long filled by 1 atm pressured air. Then, look at dose at various ‘depths’ of the shielding to determine required thickness.





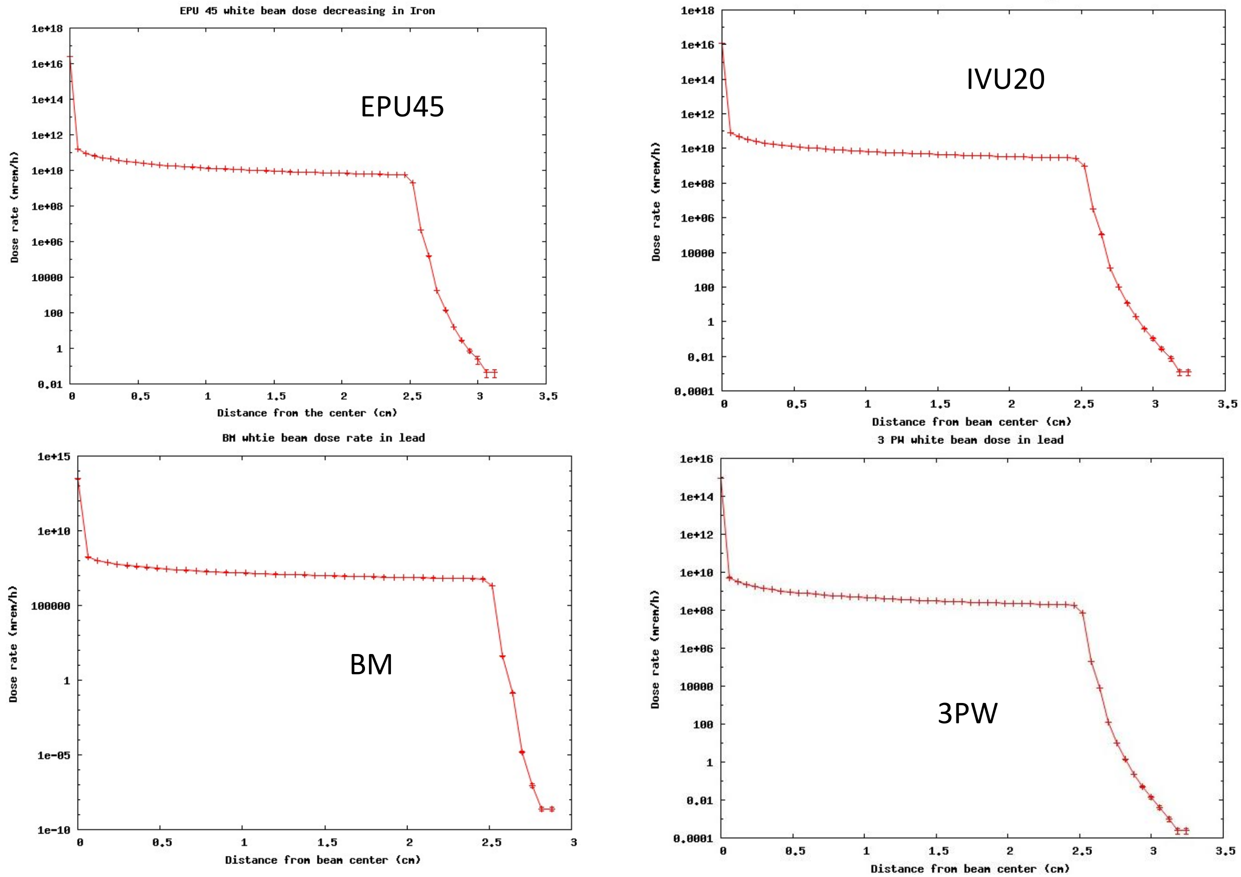


Figure A8.3-1: White beam attenuation in pipe

Results and conclusions

Table A8.3-1: Required Lead Thickness to Decrease Dose Rate < 0.5 mrem/h for Complete Vacuum Loss Outside of Pipe, White Beam

Source	Required shielding to decrease dose rate <0.5 mrem/h
DW100	5 mm Pb
EPU45	4 mm Pb
IVU20	4 mm Pb
BM	1 mm SS
3PW	3 mm Pb

Comparing with GB calculation, GB dominates the white beam transport pipe thickness (5 to 7 mm Pb required for a 10 m to 20 m long pipe).

Section 2: Primary bremsstrahlung scattering calculations with FLUKA (air scatterer)

Source

3GeV maximum energy primary bremsstrahlung beam (Appendix A) normalized to 17μW total power that corresponds to a 15.5m straight source at 10^{-9}torr.

Geometry

The study used a 20 m long, 2 inch diameter stainless steel beam pipe with 1 mm thick wall. The pipe is filled with air at 1 atmosphere. The bremsstrahlung beam is centered on pipe axis. The beam does not touch the beam pipe.

Results & Conclusions

In essence, the air interacts with the bremsstrahlung cone and creates a secondary bremsstrahlung cone that is slightly wider than the primary one. As long as the secondary cone is confined within the pipe, there is little dose outside. However, once the secondary cone hits the beam pipe, significant dose results. The dose rate goes up linearly because the dose comes from all the scattering that occurs upstream.

Based on the above, the recommended shielding for air scattering in white beam transport pipe is 7 mm Pb for the ID beamline. Although the dose level is very slightly over 0.05 mrem/hr near the end of the 20 m long transport (figure A8.3-3), this level is acceptable because air in the transport pipe is not a normal operating condition.

For the BM/3PW, the recommended shielding is 5 mm Pb (figure A8.3-4).

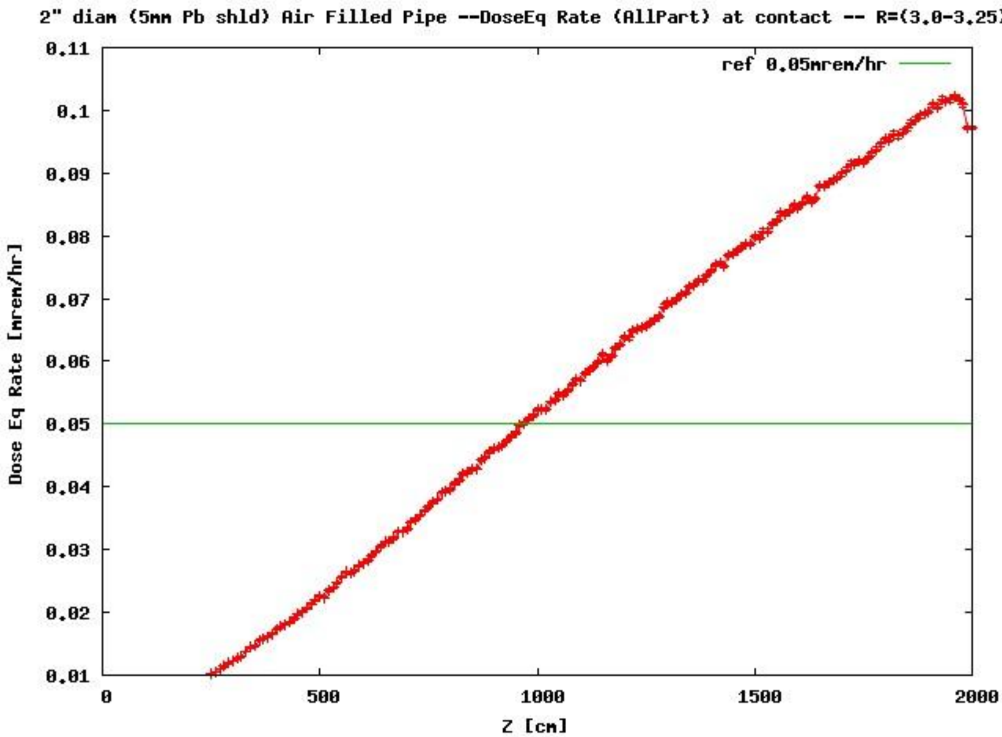


Figure A8.3-2: Contact (on surface of pipe) dose rates as a function of distance along the shielded 5 mm Pb pipe for an ID beamline

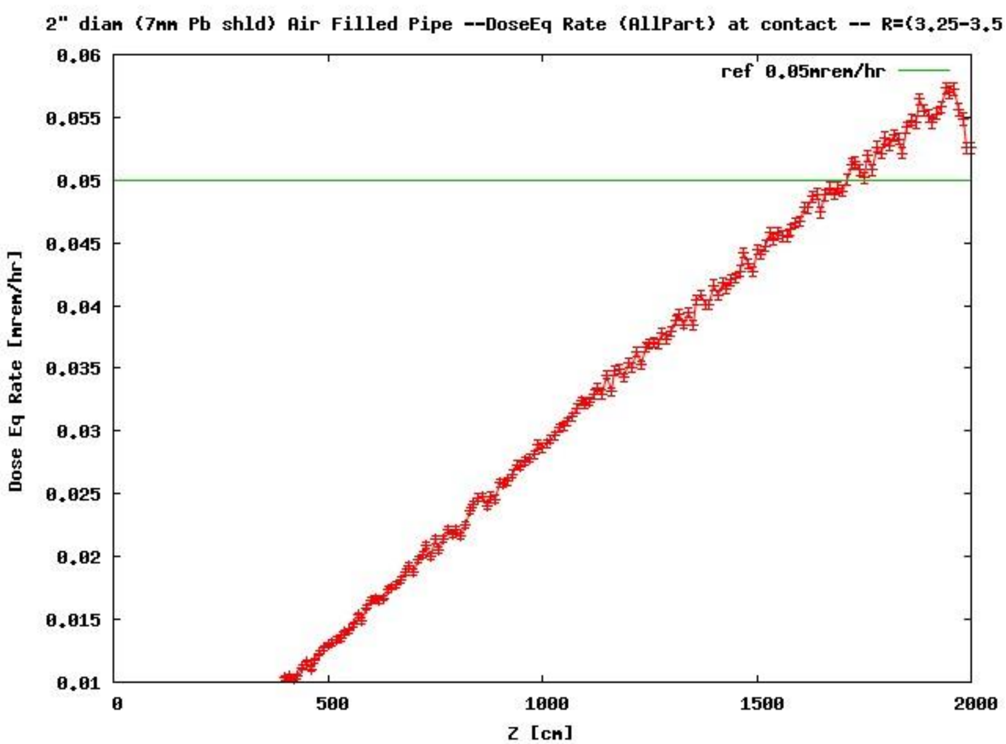


Figure A8.3-3: Contact (on surface of pipe) dose rates as a function of distance along the shielded 7 mm Pb pipe for an ID beamline.

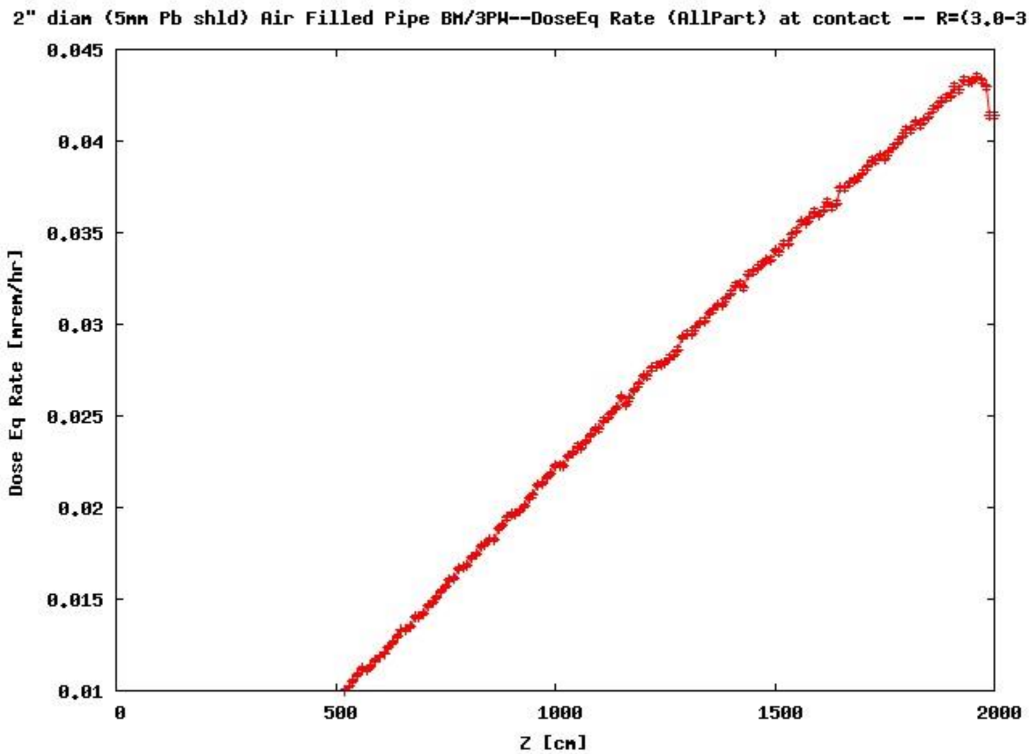


Figure A8.3-4: Contact (on surface of pipe) dose rates as a function of distance along the shielded 5 mm Pb pipe for a BM/3PW beamline.

Section 3: Synchrotron white beam Cu target scattering
Solid Scatterer in white beam

For solid scatterers, the required white beam beam transport pipe thickness is calculated by STAC8. The electron beam energy and current are 3 GeV and 500 mA in the calculation.

Source

The white beam source parameters are listed in Table A6.4-1: DW 100, IVU 20, EPU 45, BM and 3PW.

Geometry and approach

A 1" radius pipe with 1 mm Stainless Steel (SS) is wrapped by thick Pb. The dose rate is calculated by STAC8 at the surface of the shielding. The target is a 1.5 cm radius and 1 cm thick cylinder Cu or Silicon with SR perpendicular hitting the surface.

Results and conclusions

Based on STAC8 calculation, the required shielding is listed for white beam sources in Table A8.3-2.

Table A8.3-2 required shielding for white beam transport based on synchrotron white beam and copper scatterer

Source	Target	Required shielding to decrease dose rate <0.05 mrem/h
DW100	Cu	14 mm Pb
EPU45	Si	9 mm Pb
IVU20	Si	9.5 mm Pb
BM	Si	0.5 mm Pb
3PW	Si	7 mm Pb

Note for solid scatterer in transport pipe, the shielding is dominated by gas bremsstrahlung (GB) scattering (see below section 4).

Section 4: Primary bremsstrahlung scattering calculations with FLUKA (copper scatterer)

Source

3GeV maximum energy primary bremsstrahlung beam (Appendix A) normalized to 17µW total power that corresponds to a 15.5m straight source at 10^{-9}torr.

Geometry

The study used a 20 m long, 2 inch diameter stainless steel beam pipe with 1 mm thick wall. The beam pipe is in vacuum. A copper scatterer (3 cm x 3 cm x 1 cm thick) was positioned at Z=10 m, flat face perpendicular to the beam. The bremsstrahlung beam is centered on pipe axis and the radius of the beam spot on the Cu target is 8.4mm. The beam does not touch the beam pipe. (Figure A8.3-5)

The pipe is shielded by a layer of Pb. The calculations assessed the contact dose equivalent rate, on beam pipe surface, with various thickness of Pb shielding the pipe.

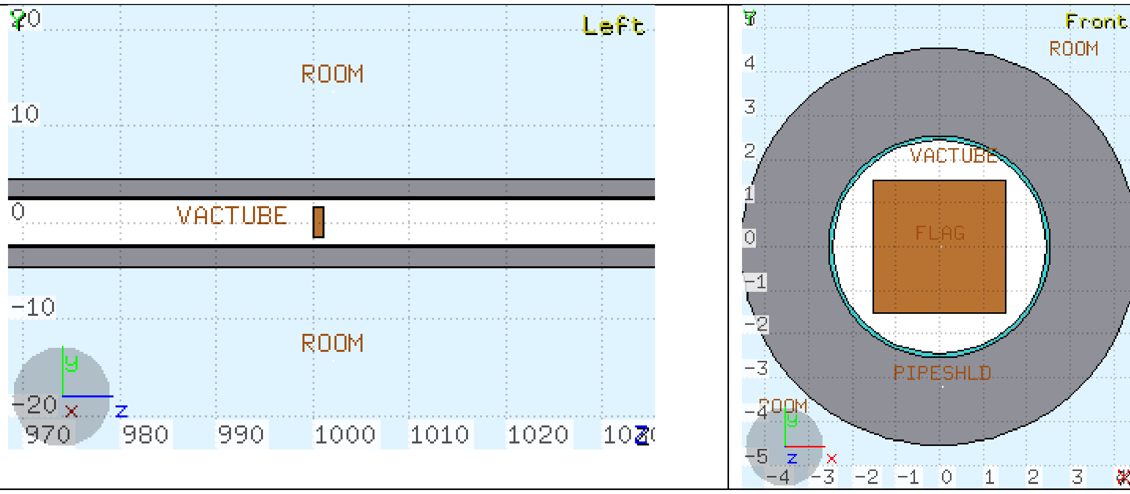


Figure A8.3-5: FLUKA simulation geometry. Longitudinal and transversal sections.

Results & Conclusions

As expected, the secondary bremsstrahlung scattered from the copper target creates significant dose that requires more than 10 cm of Pb shielding to reduce the dose rates below the 0.05 mrem/hr limit (figures A8.3-6 to A8.3-9). As such, a solid scatterer in a white beam transport is greatly discouraged. In the event that the scatterer is necessary, either a small shielded enclosure and/or an exclusion zone may be needed.

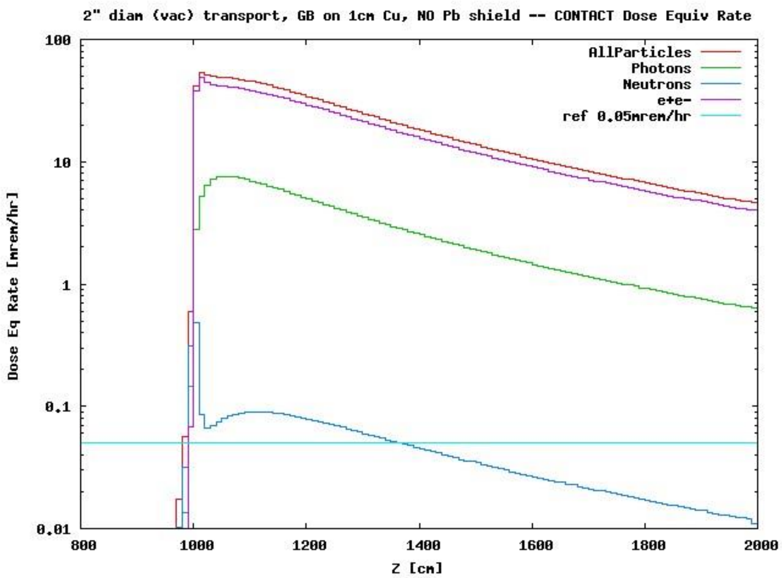


Figure A8.3-6: Contact dose equivalent rate on beampipe surface without pipe shielding.

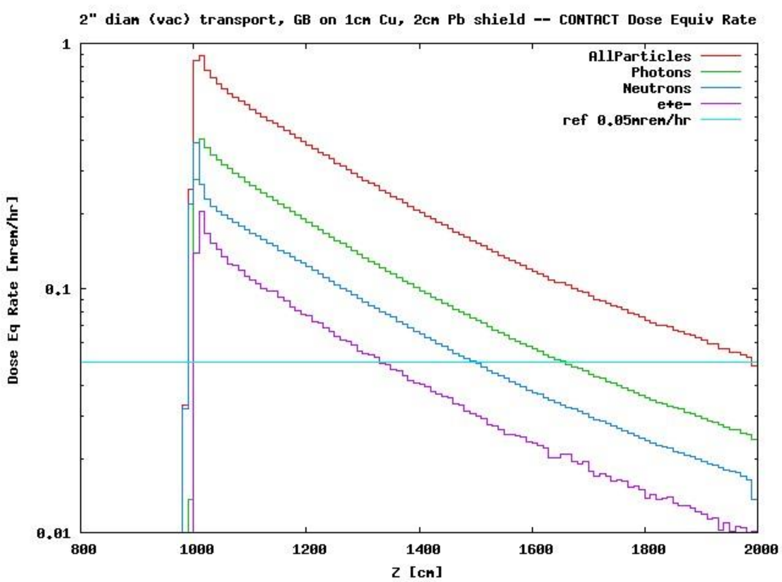


Figure A8.3-7: Contact dose equivalent rate on beampipe surface with 2cm Pb pipe shielding.

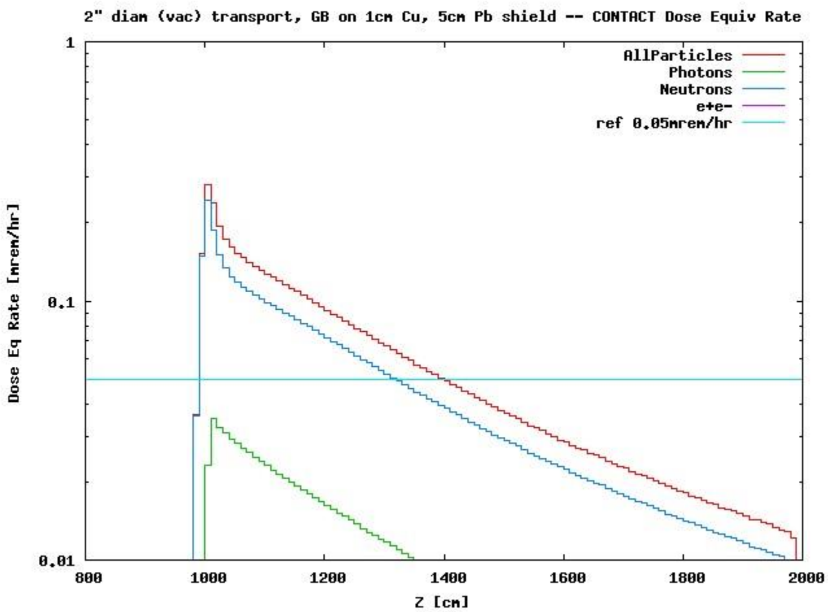


Figure A8.3-8: Contact dose equivalent rate on beampipe surface with 5cm Pb pipe shielding.

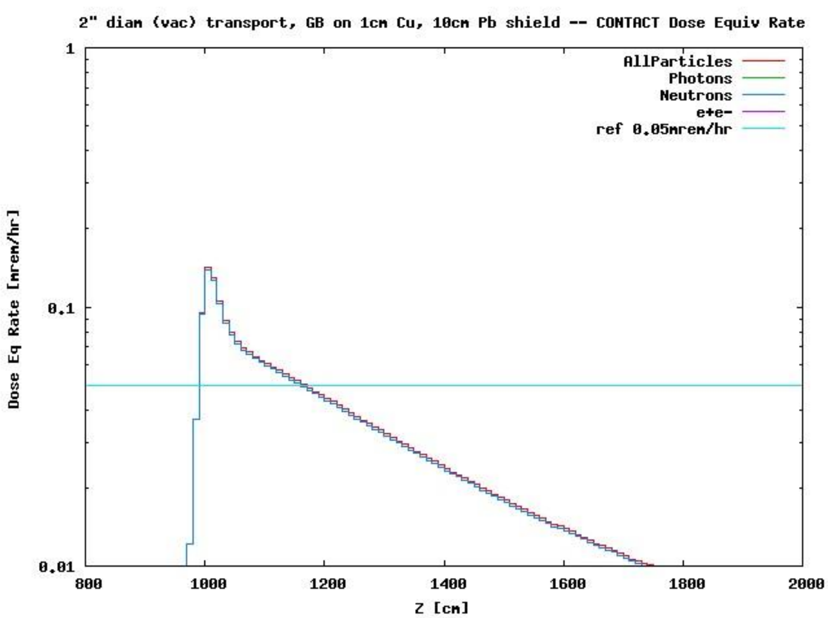


Figure A8.3-9: Contact dose equivalent rate on beampipe surface with 10cm Pb pipe shielding.

Appendix 9.1: Basis for shielding secondary bremsstrahlung shielding from mirror

Source

3GeV maximum energy primary bremsstrahlung beam (Appendix A) normalized to 17µW total power that corresponds to a 15.5m straight source at 10^{-9}torr. The radius of the beam spot at the target location is approx. 5mm.

Geometry

The study used a simplified rectangular enclosure, 10m long, terminated by a 5cm thick Pb downstream wall without any apertures. The lateral wall is located 1.5m from the beam axis and is constructed of 18mm Pb. The roof of the enclosure is located 2.0m above the beam plane and is made of 6mm Pb.

The target consists of a Si mirror 3 cm x 4 cm x 100 cm at 0.25 deg incidence angle. Mirror located from Z=250 cm to Z=350 cm and reflects the beam upwards.

A white beam stop was modeled as 0.75 cm radius x 3 cm long copper cylinder, located from Z=650 cm to 653 cm. The distance away from mirror was chosen such that it provides sufficient clearance between pink beam and bremsstrahlung cone.

A primary bremsstrahlung stop was modeled as a W cylinder 20 cm long by ~ 6 cm diameter. The 6 cm diameter was chosen to obey the 3 Moliere radius rule. For W, 3 Moliere radius = 24 mm. Therefore, the diameter of the W stop should be: 2 x (24 mm + 5 mm) = 58 mm ~ 6 cm. The bremsstrahlung stop is located from Z = 654 cm to 674 cm.

Section 1: Assessment of dose with standard white beam enclosure downstream wall of 50 mm Pb

Results show that the dose rates on the roof and on the lateral wall are comfortably within limits for this white beam enclosure dimension (figures A9.1-5 and A9.1-6). However, the secondary bremsstrahlung scattering presents a problem beyond the downstream wall of the white beam enclosure (figures A9.1-1 to A9.1-4).

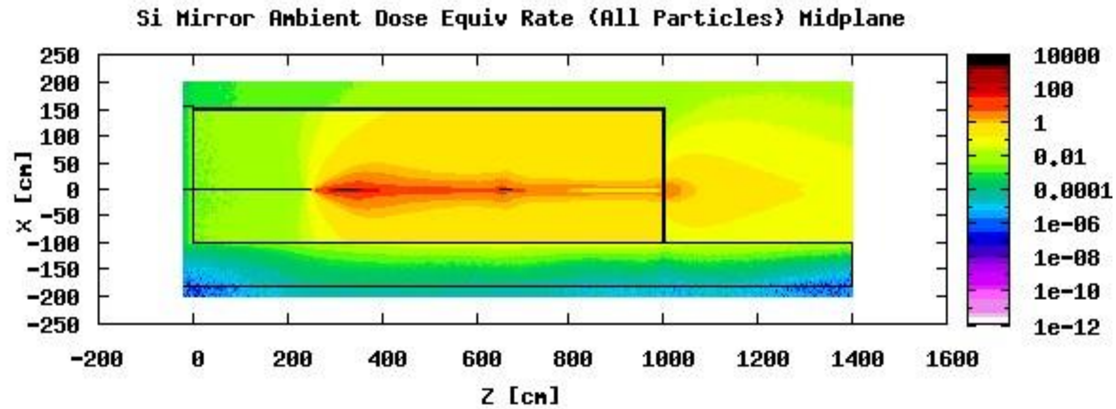


Figure A9.1-1: Midplane (top view) ambient dose equivalent rate distribution.

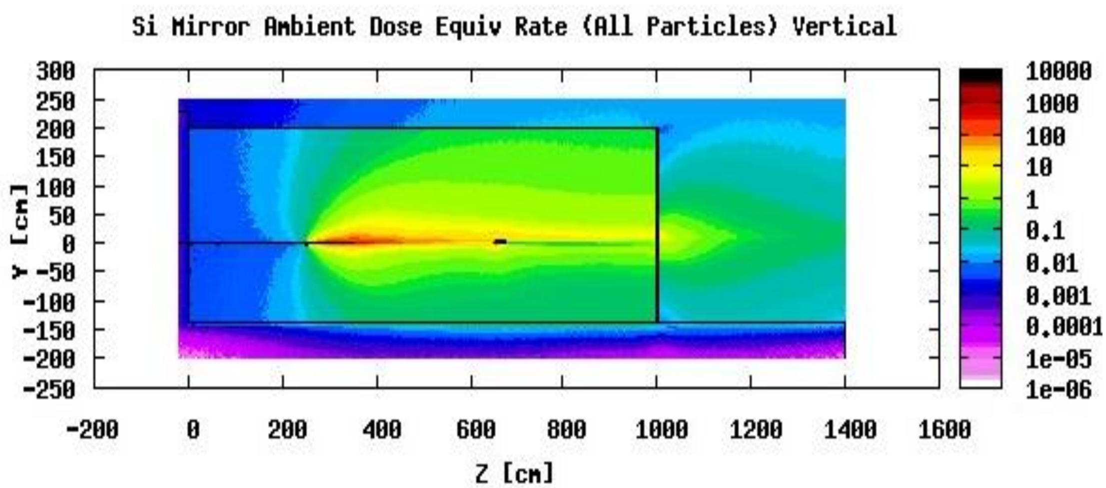


Figure A9.1-2: Vertical plane (side view) ambient dose equivalent rate distribution.

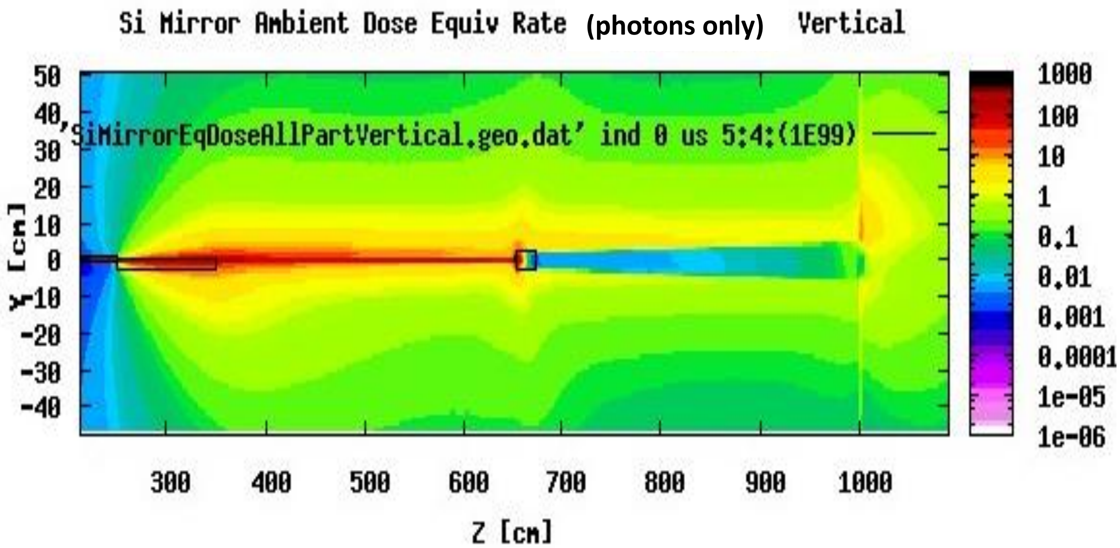


Figure A9.1-3: Vertical plane (side view) ***photons only*** **ambient dose equivalent rate distribution.**

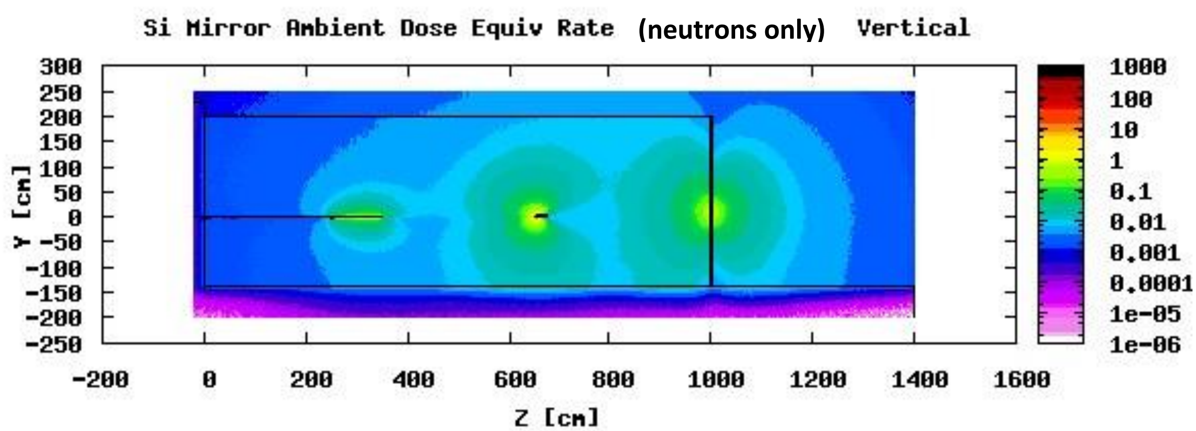


Figure A9.1-4: Vertical plane (side view) ***neutrons only*** **ambient dose equivalent rate distribution.**

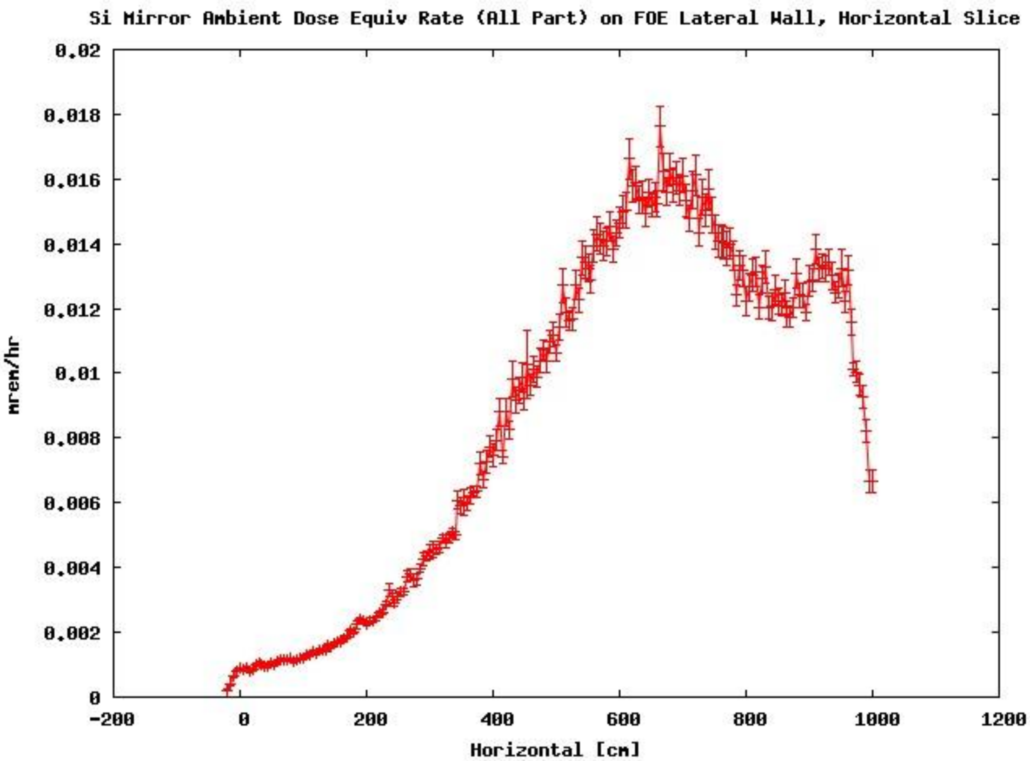


Figure A9.1-5: Ambient dose equivalent rate along the lateral wall, at midplane (horizontal) cut.

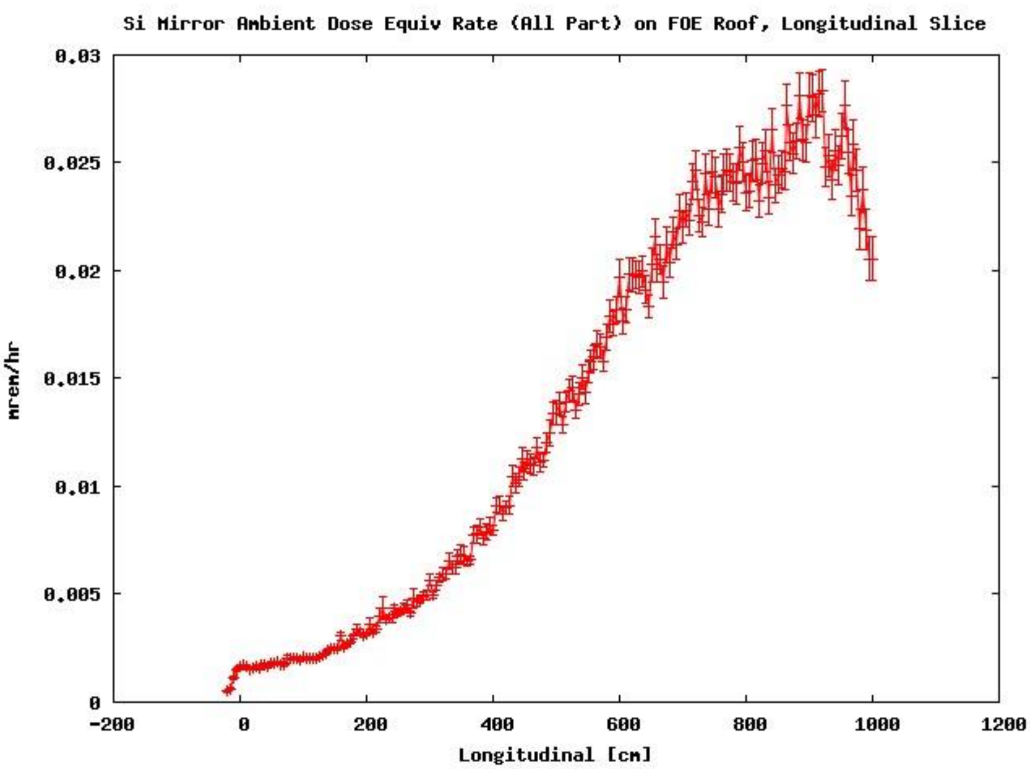


Figure A9.1-6: Ambient dose equivalent rate along the beam direction on the enclosure roof, centered on the beam center line.

Section 2: Could increasing the downstream wall thickness address the issue?

Assess the dose with variable white beam enclosure downstream wall Pb thickness.

As figures A9.1-7 to A9.1-9 indicate, behind the white beam enclosure at locations less than 1 m laterally from the center the downstream 50 mm Pb shielding is not sufficient. Close to the center even 20 cm of Pb would not be enough.

In this geometry, the distance between the mirror and the downstream wall is 7 m, so, 1 m laterally from the center at the downstream wall corresponds to ~arctan(1/7) = 8.1 deg from beam center line. *Therefore, for scattering angles larger than 8 deg the dose at downstream locations is within limits*.

Also, note that Pb is a poor attenuator of neutrons. So, unless neutron absorbers are added, in general, it is preferable to have the bremsstrahlung shielding located as far away from the downstream wall as possible.

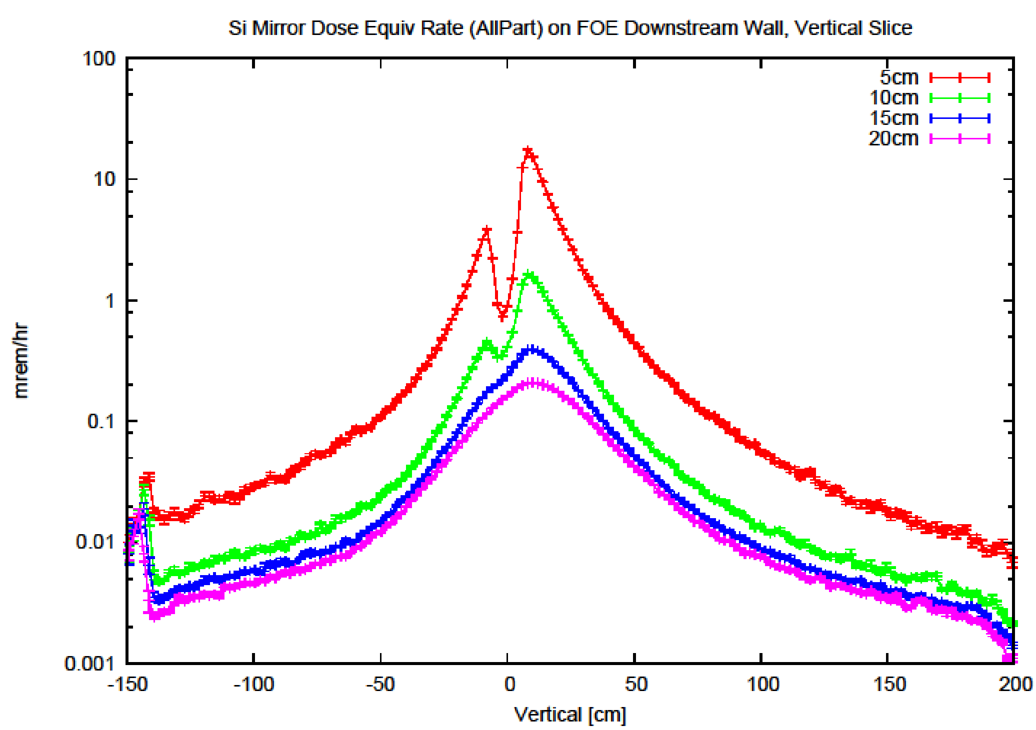


Figure A9.1-7: Dose equivalent rate on the downstream wall function of wall thickness. All particle species.

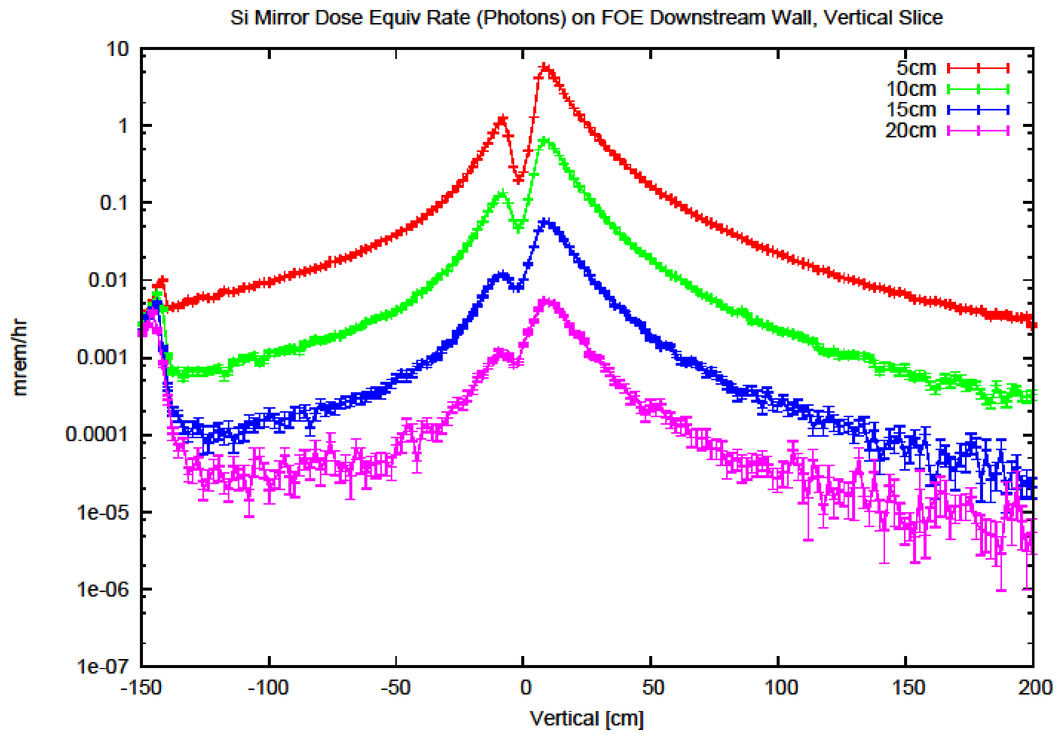


Figure A9.1-8: Dose equivalent rate on the downstream wall function of wall thickness. Photons only.

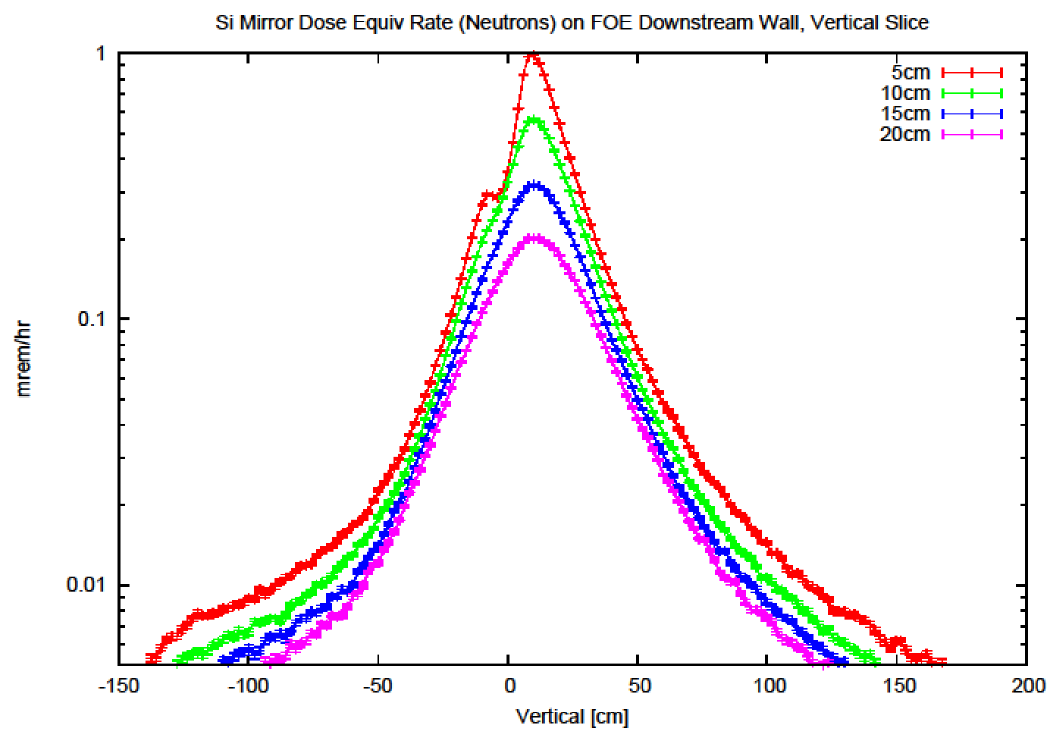


Figure A9.1-9: Dose equivalent rate on the downstream wall function of wall thickness. Neutrons only.

Section 3: Configuration of local secondary bremsstrahlung shielding

Geometry

We assess the required configuration of a local secondary bremsstrahlung shield by adding a 1 m x 1 m piece of material in the white beam enclosure, at various locations after the mirror (figure A9.1-10). We vary material thickness and material (Pb or W). We assume a 50 mm Pb white beam enclosure downstream wall.

The rest of the components remain the same, as described in the introductory section of Appendix 9.1.

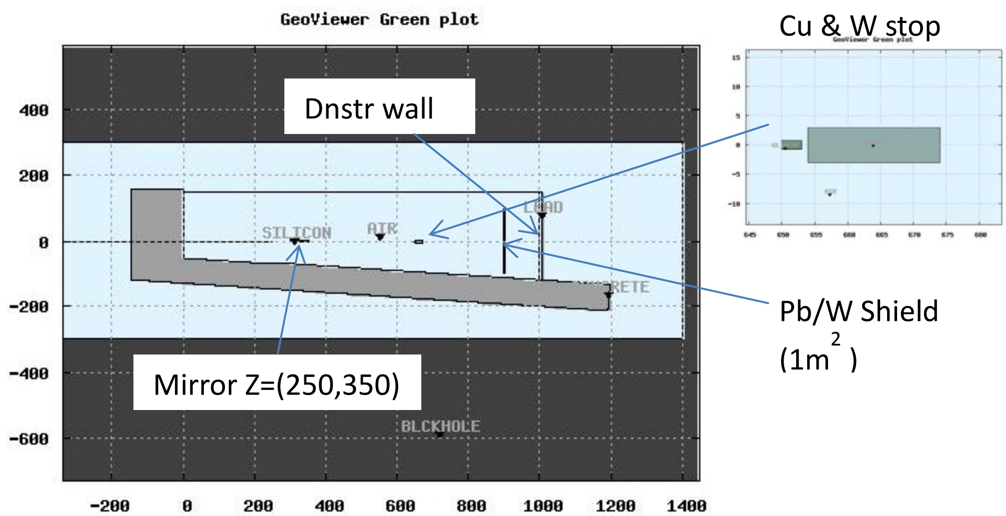


Figure A9.1-10: Geometry of the simulation. Added 1m x 1m shielding placed at various (Z) locations downstream of the mirror.

Results & Conclusions

As figures A9.1-11 and A9.1-12 indicate, for downstream lateral location between 50 cm to 100 cm from the beam, 5 cm of additional Pb are needed. This corresponds to between 4 deg and 8 deg scattering angle from the mirror. Between 25 cm and 50 cm, 7 cm Pb is needed. This corresponds to between 2 deg and 4 deg. Below 25 cm (equivalent to about 2 deg), 9 cm Pb is needed. For W, the corresponding values are 4 cm, 5 cm and 6 cm (~ 2/3 of Pb thickness).

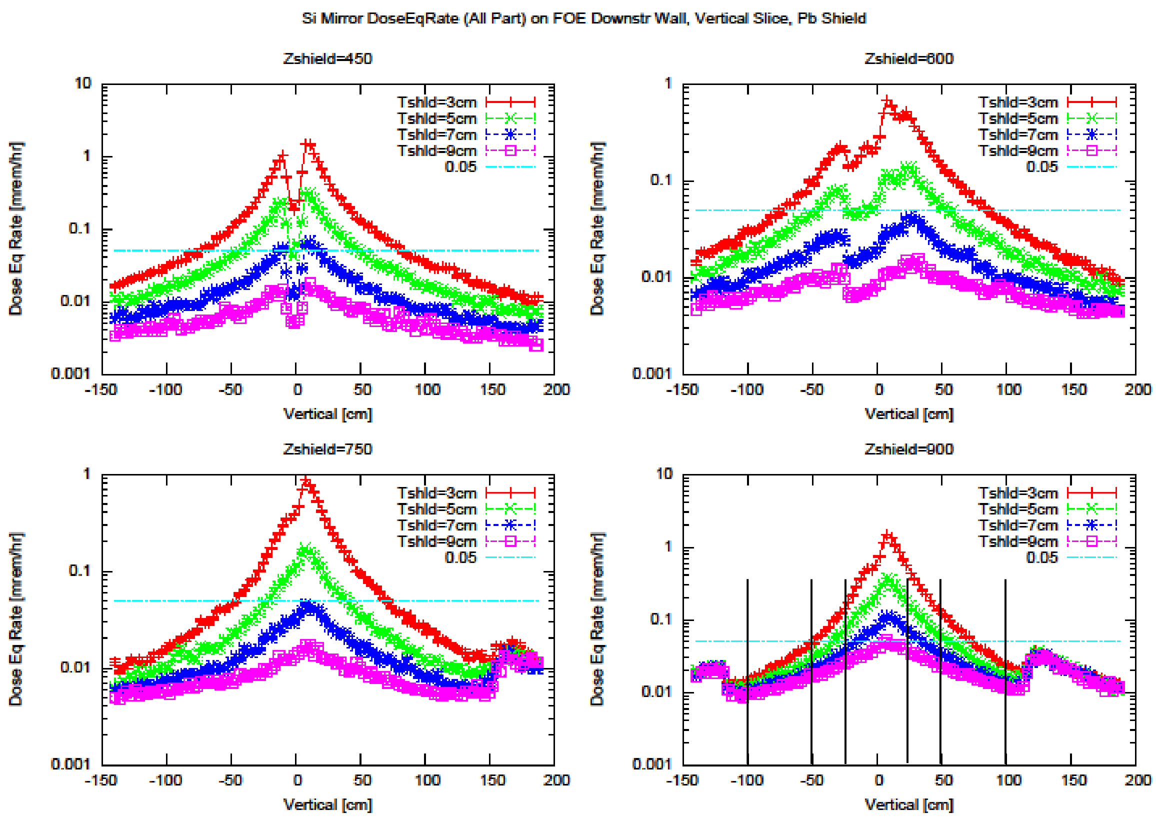


Figure A9.1-11: Dose rates on the white beam enclosure downstream wall for Pb local shield, as a function of shield location and thickness. The white beam enclosure downstream wall is 50 mm Pb.

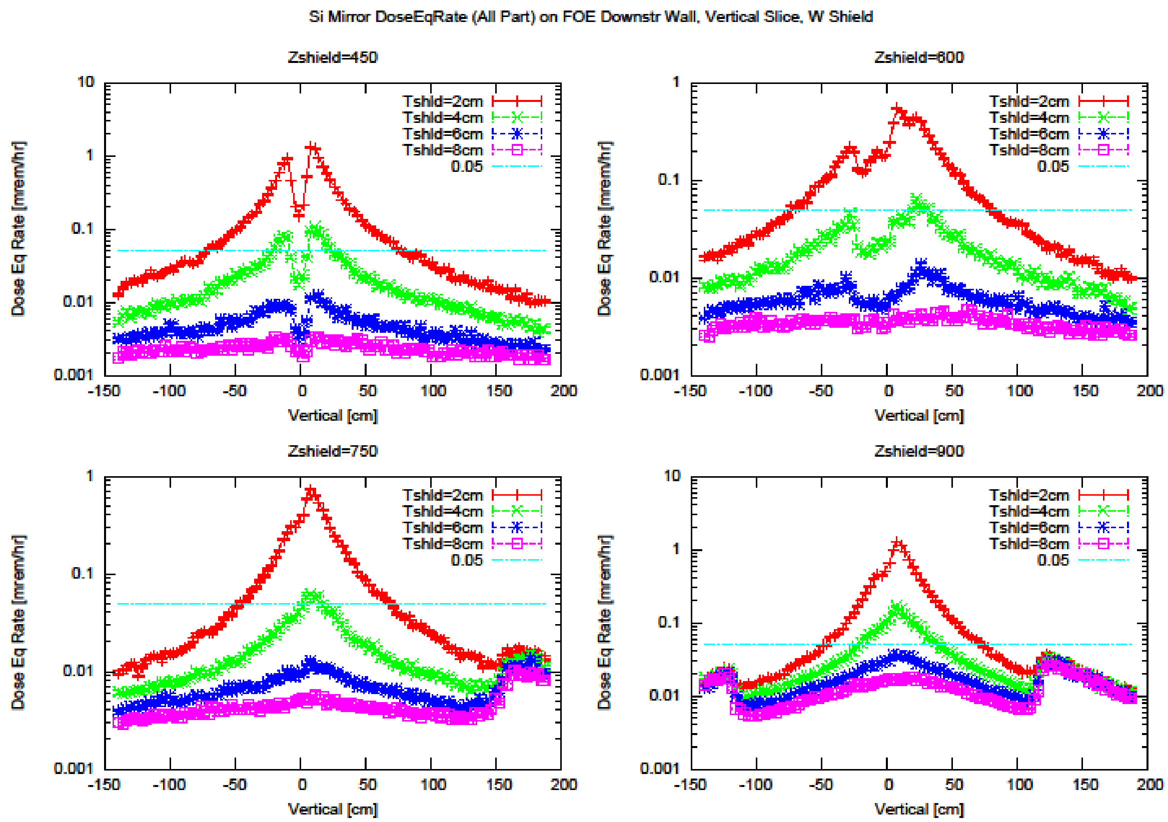


Figure A9.1-12: Dose rates on the white beam enclosure downstream wall for W local shield, as a function of shield location and thickness. The white beam enclosure downstream wall is 50 mm Pb.

The complex dependence on shield location should be noted. Also, these results may seem at odds with previous (Section 2) simulation without the secondary shield, which suggest that even 20 cm of white beam enclosure downstream thickness is not sufficient to stop the secondary bremsstrahlung; while the current simulations suggest that the total amount of lead required is ~ 9 cm + 5 cm (white beam enclosure back wall) = 14 cm Pb. The difference comes from the location of the shields relative to the downstream. In the previous scenario, all the neutrons are created at the downstream wall itself and since Pb is a poor attenuator of neutrons, the dose immediately behind the white beam enclosure downstream is high. With the deployment of secondary bremsstrahlung shielding located some distance upstream of the downstream, the neutrons are produced further upstream at the secondary shield location.

Note that in the simulation geometry, the primary bremsstrahlung stop shields up to 30 mm/3 m = 10 mrad ~ 0.56 deg.

Section 4: "Double-shielding"

Geometry

In the simulations described in Section 3 the central rays see *both* the primary bremsstrahlung Cu/W stop and the additional secondary shielding. To check that this 'double-shielding' of the central rays are not necessary, we made an aperture in the secondary shielding. The diameter of the aperture is 1 mm smaller than the diameter of the W primary bremsstrahlung stop. The secondary shield is 1m x 1 m x 8 cm thick Pb located at Z = 700 cm (figure A9.1-13).

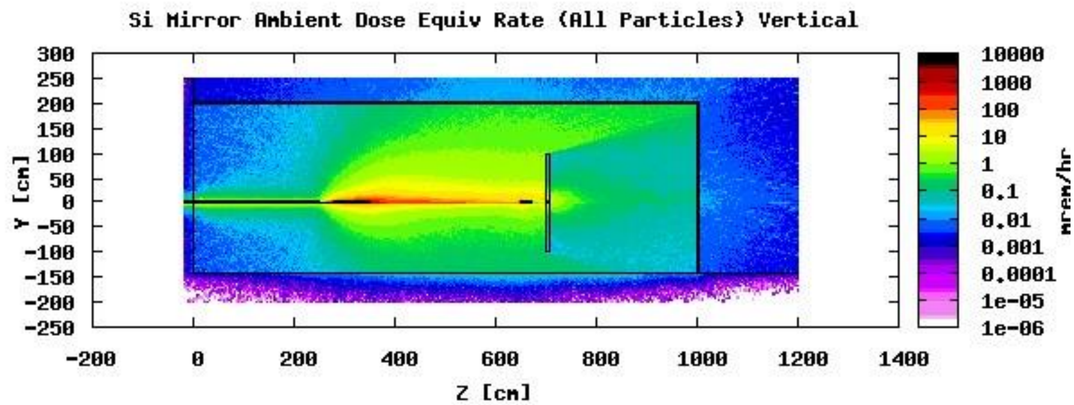


Figure A9.1-13: Geometry of the local shield with a central aperture

Results & Conclusions

Results (figure A9.1-14) confirm that *'double-shielding' in the central region is not required*. That is, one does not need to add shielding in the regions shadowed by the primary bremsstrahlung stop.

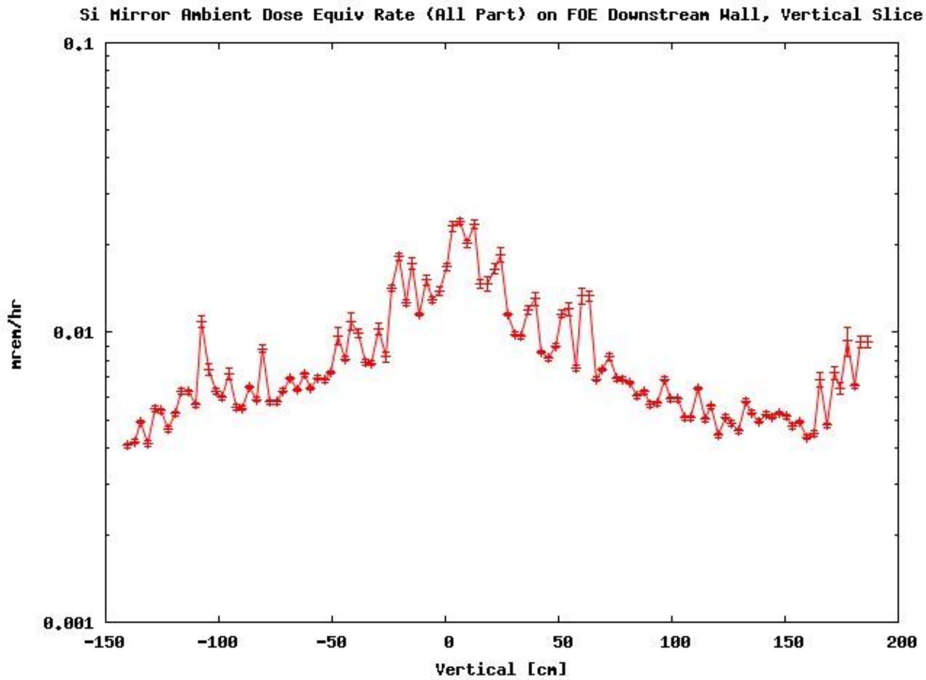


Figure A9.1-14: Dose rates on the enclosure downstream wall when the secondary shielding (8 cm Pb) contains a central aperture

Section 5: Bremsstrahlung scattering on a monochromator crystal

Geometry

The configuration is similar to the one used in Section 1 (see intro section of Appendix 9.1) except that the target is a Si monochromator 100x100x25mm located at Z=300cm and tilted 3.5deg upwards. Enclosure walls, primary bremsstrahlung and white beam stops are unchanged.

To assess the proper thickness of local secondary bremsstrahlung shielding, a different set of calculations added a 1x1m Pb wall of various thickness, placed at Z=900cm.

Results & Conclusions

As figure A9.1-15 indicates, locations more than 50cm from the beam axis require no additional shielding. With the monochromator located at 7m from the downstream wall, 50cm off beam axis correspond to atan(50/700) ~4°scattering angle from the monochromator.

Therefore: above 4° no shielding is needed, between 2° and 4° 5 cm Pb is needed, and at less than 2° 7 cm of Pb is needed (figure A9.1-16).

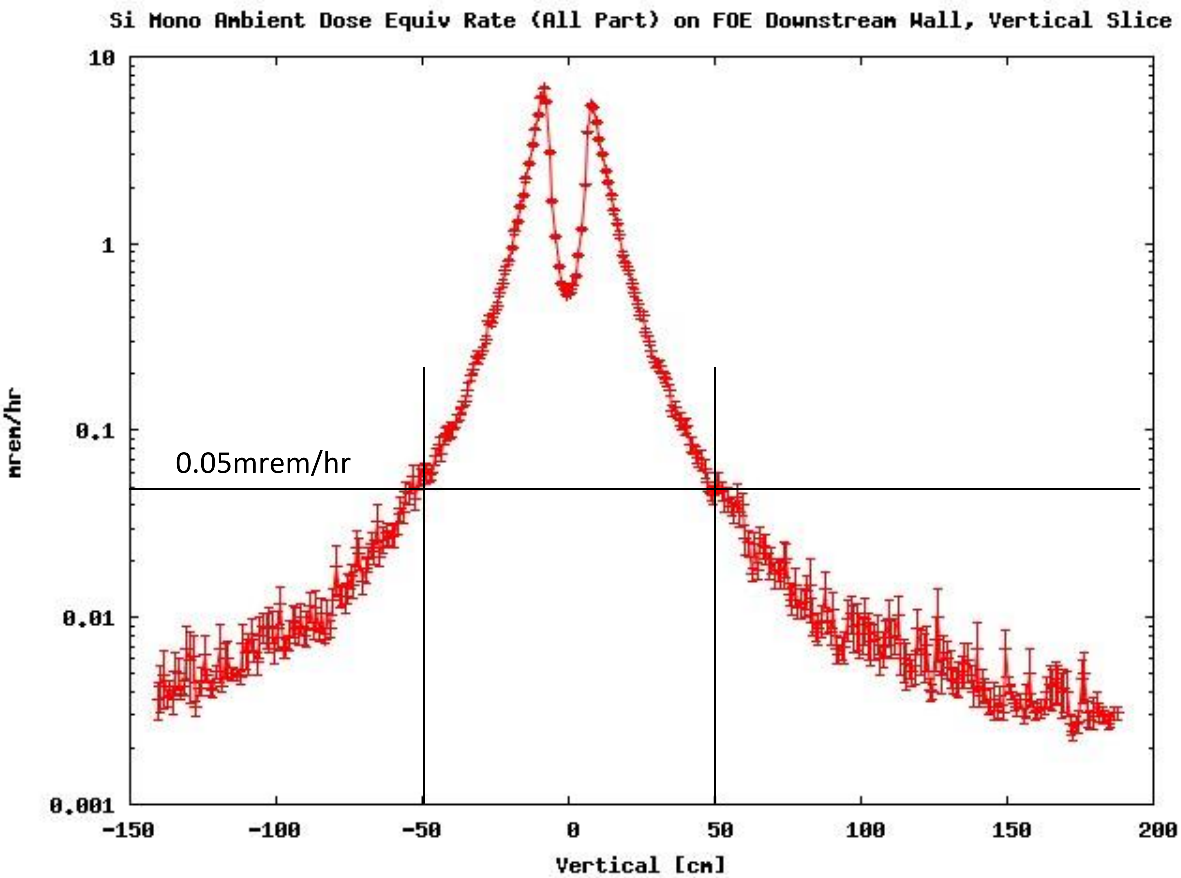


Figure A9.1-15: Dose rate behind white beam enclosure with no added shielding for secondary bremsstrahlung from monochromator.

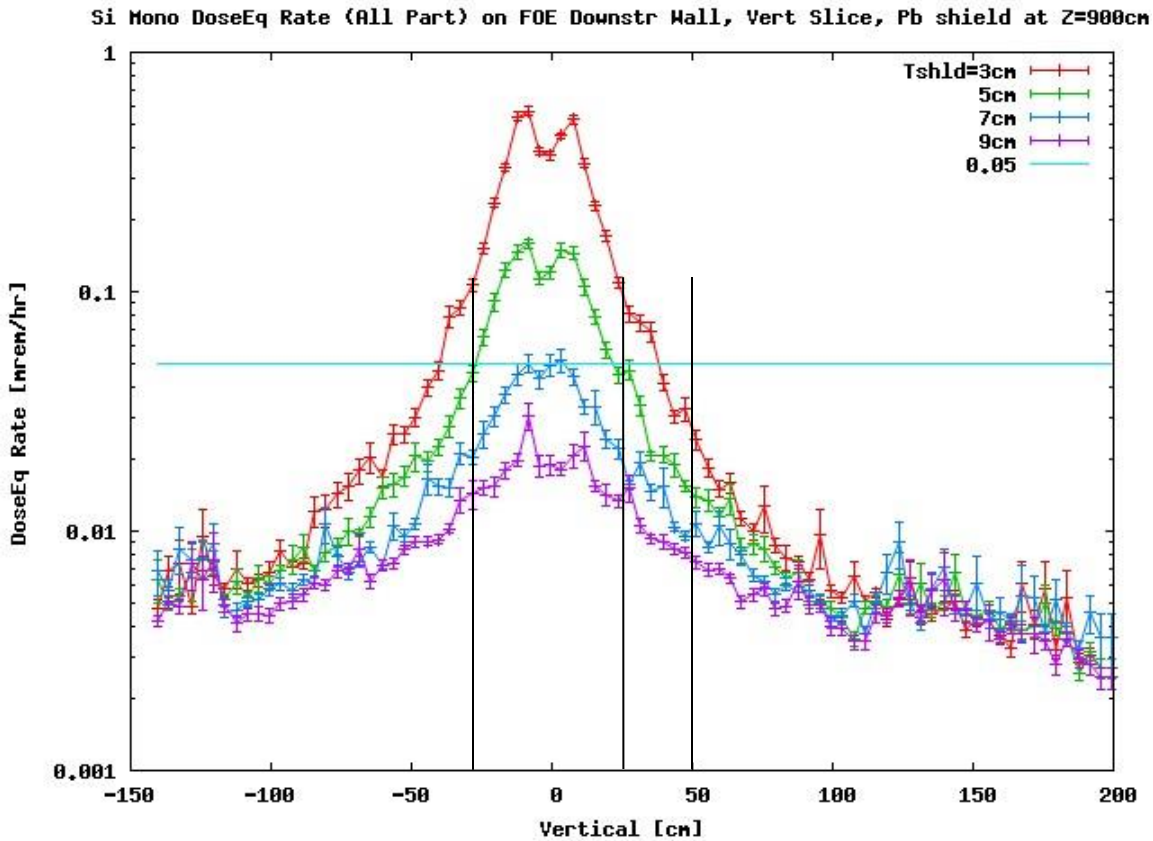


Figure A9.1-16: Dose rate behind white beam enclosure with different thickness of Pb shielding at 1 m upstream of the white beam enclosure downstream wall.

Section 6: Bremsstrahlung scattering on a Cu target

Geometry

The configuration is similar to the one used in Section 1 (see intro section of Appendix 9.1) except that the target is a Cu cylinder 3cm diameter, 3cm length, located at Z=300cm. Enclosure walls, primary bremsstrahlung and white beam stops are unchanged.

To assess the proper thickness of local secondary bremsstrahlung shielding, a different set of calculations added a 1x1m Pb wall of various thickness, placed at Z=900cm.

Results & Conclusions

As figure A9.1-17 indicates, location more than ~100cm from the beam axis require no additional shielding (effectively the limit is about 80-90cm, but a safety margin should be added making the boundary ~100cm similar to the Si mirror scatterer). With the Cu target at 7m from the downstream wall, ~100cm off beam axis corresponds to atan(100/700)~8° scattering angle from the Cu target.

The resulting dose rates in the presence of local Pb secondary bremsstrahlung shielding (figure A9.1-18) indicate that for downstream lateral location between 50 cm to 100 cm from the beam, 5 cm of additional Pb are needed, which correspond to scattering angles between 4° and 8°. Between ~30cm and 50 cm, 7 cm Pb is needed. This corresponds to scattering angles between ~2.5° and 4°. Below 25 cm (equivalent to about 2.5°) 9 cm Pb is needed.

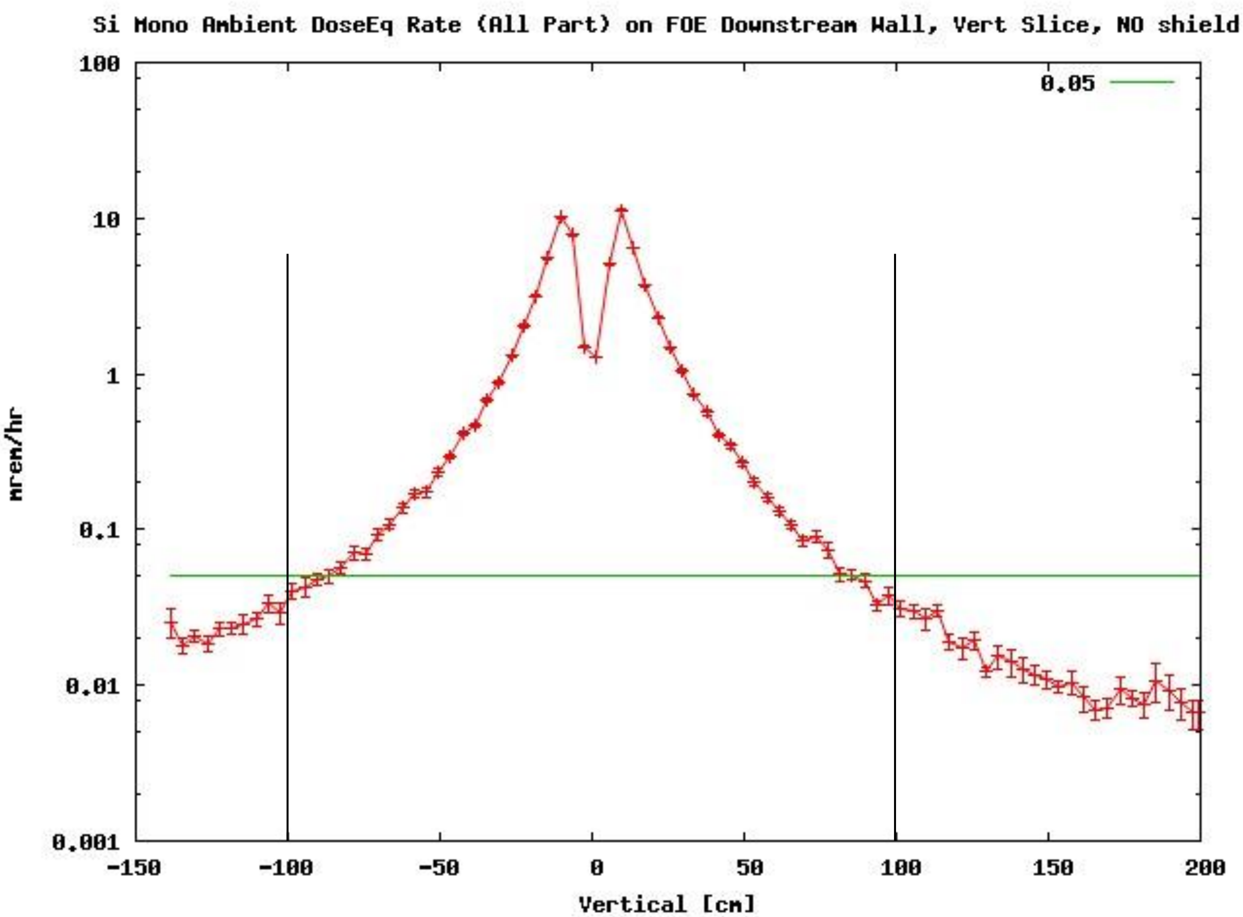


Figure A9.1-17: Dose rate behind white beam enclosure without added shielding for secondary bremsstrahlung.

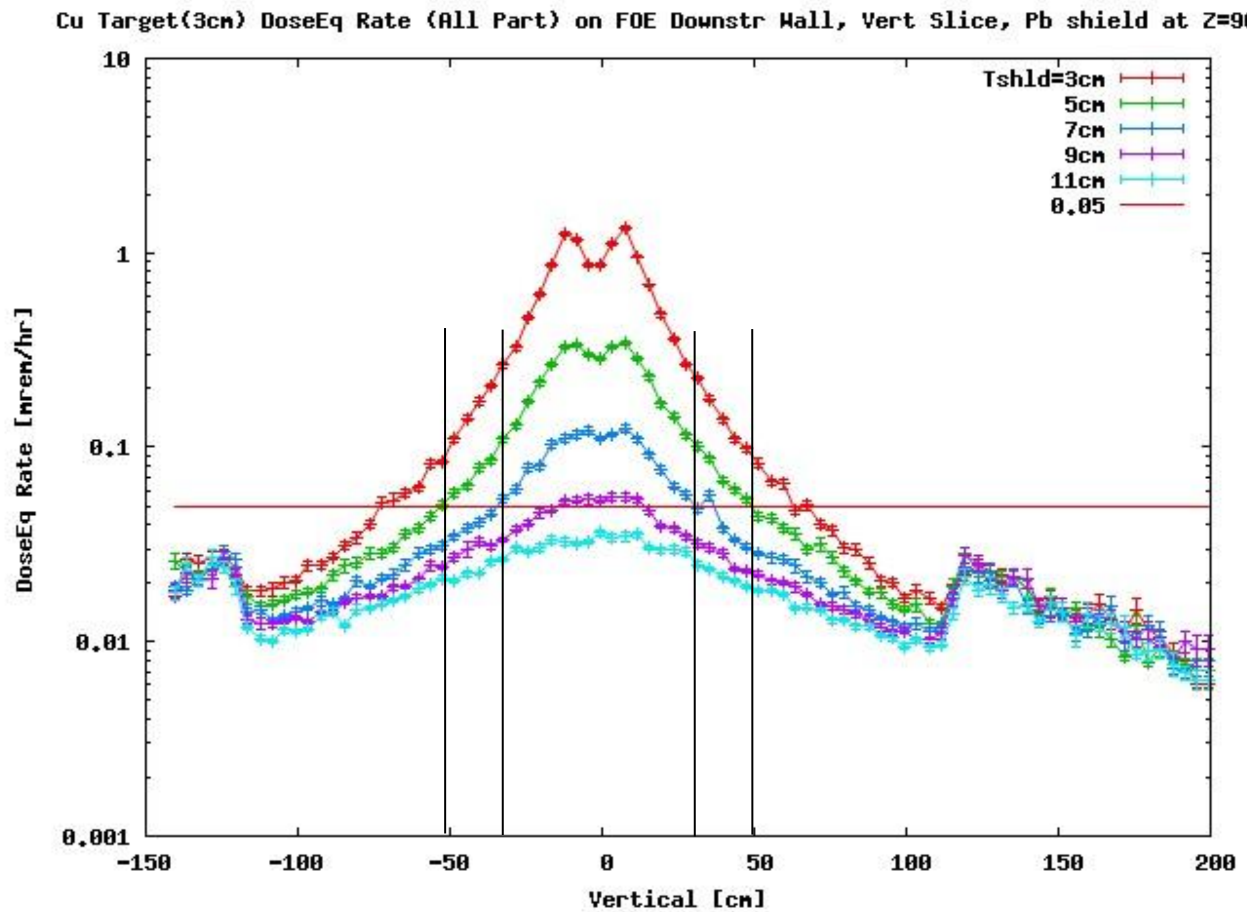


Figure A9.1-18: Dose rate behind white beam enclosure with different thickness of Pb shielding at 1 m upstream of the white beam enclosure downstream wall.

Appendix 9.2: Exclusion zones

Calculate how large an extent an interlocked exclusion area downstream of a white beam station needs to be so that the showers created by secondary bremsstrahlung at the white beam station downstream wall reach dose rates below 0.05 mrem/hr.

Geometry

The study used a 10m long enclosure with 5cm thick Pb downstream wall (no apertures), 18mm thick Pb lateral wall located at 1.5m from beam axis, 10mm roof at 2m above beam axis.

The scattering target was a 3x4cm 1 m long Si mirror at 0.25deg, reflecting the beam upward.

The white beam and bremsstrahlung stop were modeled as Cu and W cylinders of 1.5cm/3cm and 6cm/20cm diameter/length, respectively, located at Z~650cm (3m downstream of the scatterer).

Results & Conclusions

The ambient dose equivalent rate distribution downstream of the white beam enclosure was projected on a horizontal plane (at beam axis level) to assess the required transversal extent of the exclusion zone (figures A9.2-1 and A9.2-2). In addition, a vertical beam plane projection (figures A9.2-4 and A9.2-5) was constructed to determine, in conjunction with the horizontal projection, the longitudinal extend of the exclusion. One has to remember that the vertical mirror scattering will deflect the peak downstream dose rate to a location above the horizontal beam plane, thus outside (above) the 2d horizontal projection mentioned before (see the detail in figure A9.2-5). To account for it, one has to rely on the vertical dose rate projection to properly capture the maxima and yield a correct assessment of longitudinal extent of the exclusion zone.

To guide the viewer a contour line at a dose rate of 0.05mrem/hr was added to the plots in figures A9.2-1 to A9.2-6.

In addition, to help with determining the location where the dose rate drops below the 0.05mrem/hr limit, figures A9.2-3 and A9.2-6 contain the value of the *maximum* dose rate function of the longitudinal coordinate (Z). For each of these plots we started with one of the 2d dose rate distributions – horizontal or vertical, as described above, and for each Z value we plotted the *maximum dose rate value,* no matter where transversally on the 2d projection it occurred.

As shown in figures A9.2-2 and A9.2-6 one has to exclude at least 8m downstream before the dose rate is reduced below 0.05 mrem/hr. Laterally, the exclusion zone needs to extend about 1.3 m away from the beam axis. Note that this is a worst case scenario that whereby there is a maximum amount of secondary bremsstrahlung hitting the downstream white beam enclosure.

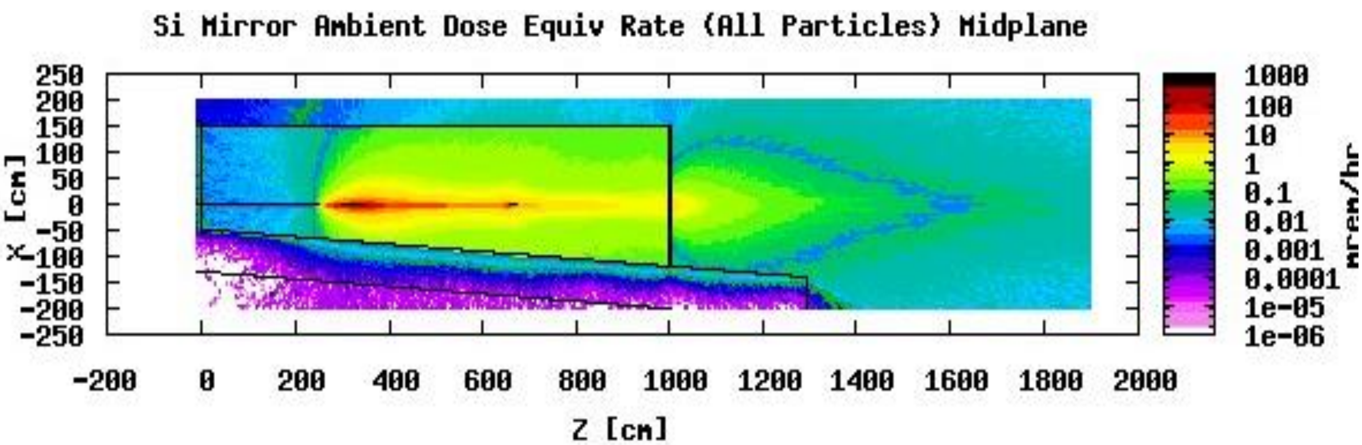


Figure A9.2-1: Midplane (top view) ambient dose equivalent rate. All particles. The 0.05mrem/hr contour line is shown in blue.

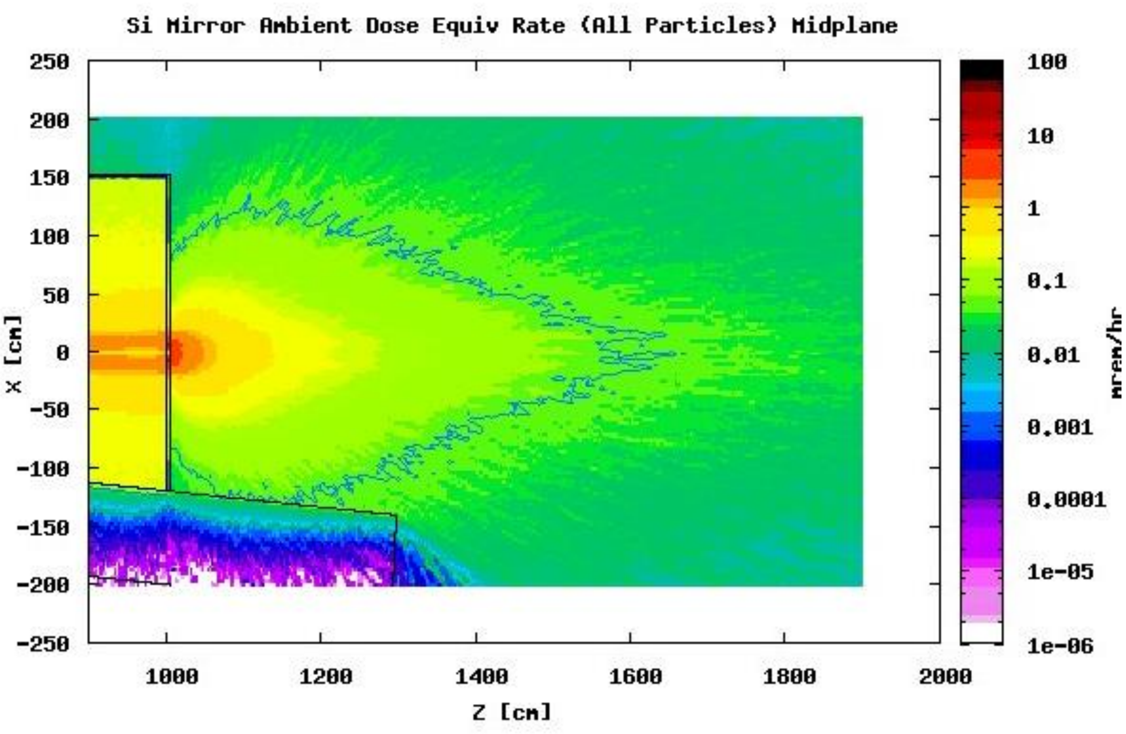


Figure A9.2-2: (Detail area) Midplane (top view) ambient dose equivalent rate. All particles. The 0.05mrem/hr contour line is shown in blue.

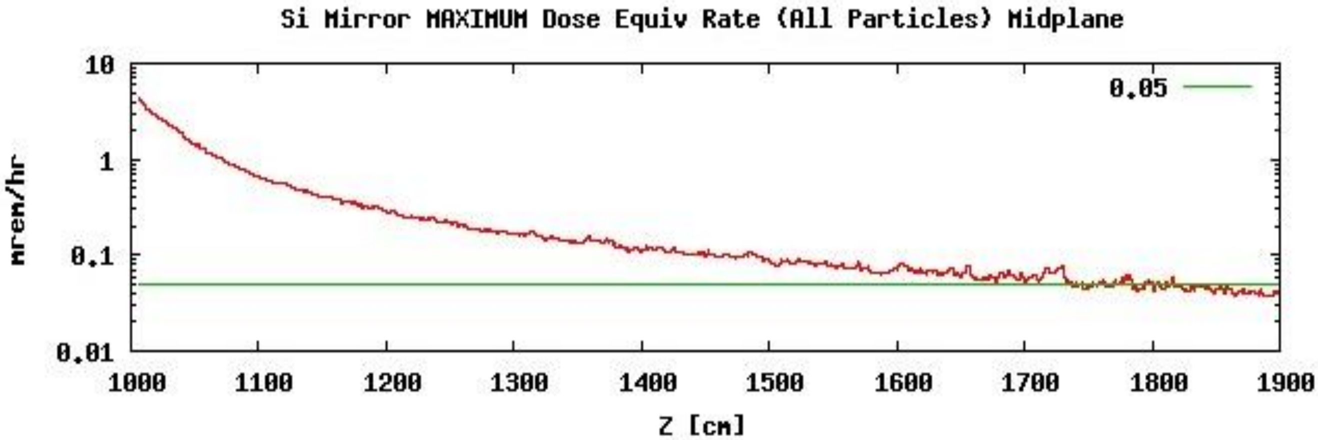


Figure A9.2-3: Maximum dose rate function of the longitudinal coordinate (Z).

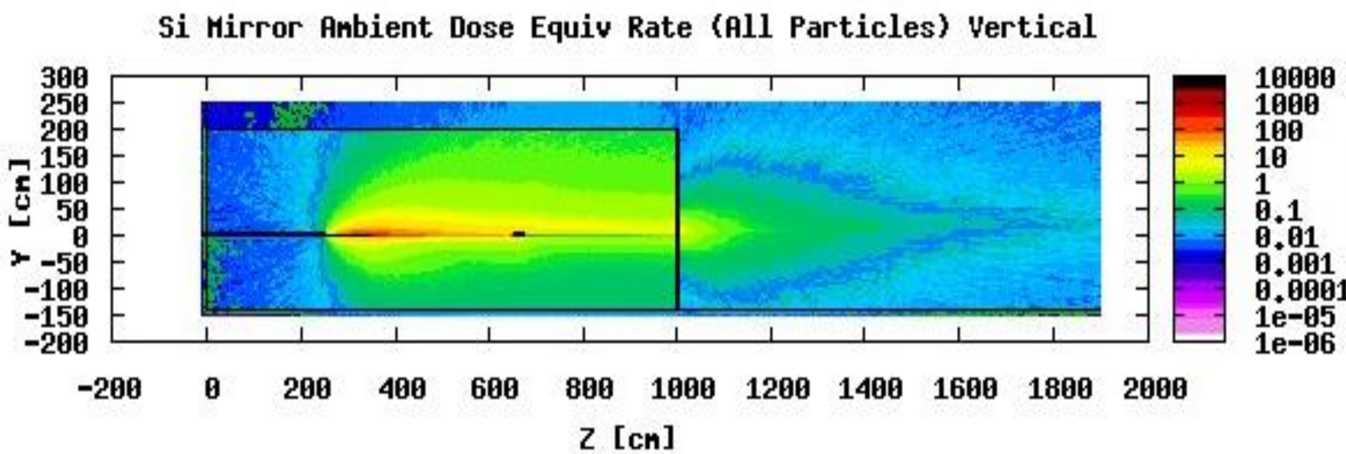


Figure A9.2-4: Vertical plane (side view) ambient dose equivalent rate. All particles. The 0.05mrem/hr contour line is shown in blue.

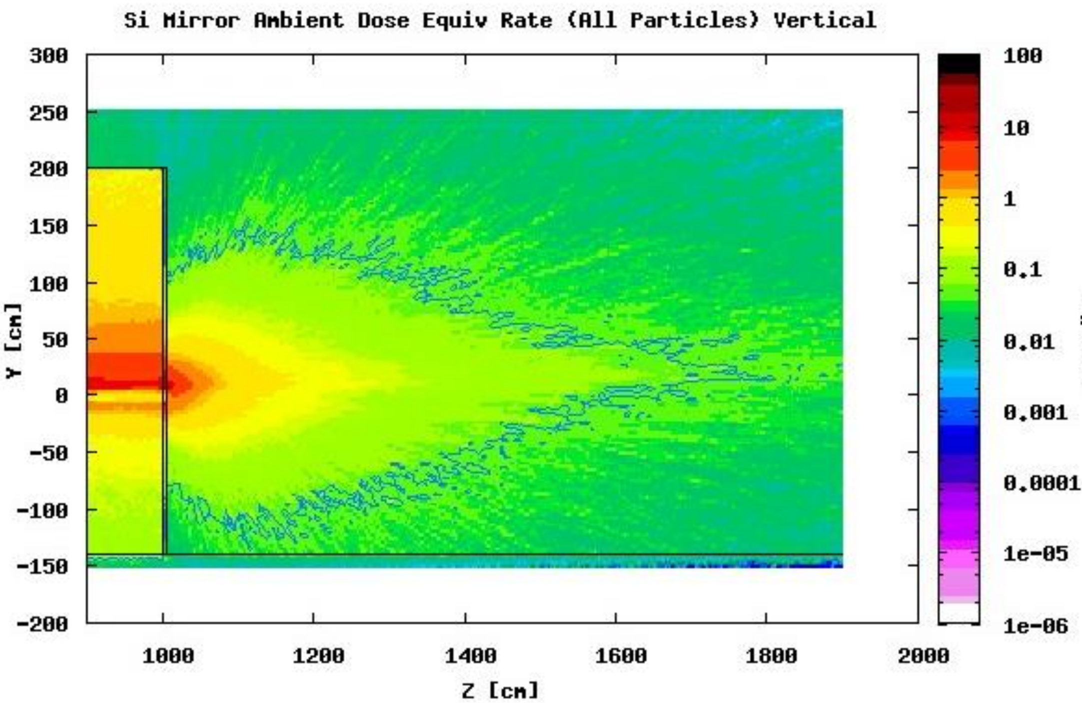


Figure A9.2-5: (Detail area) Vertical plane (side view) ambient dose equivalent rate. All particles. The 0.05mrem/hr contour line is shown in blue.

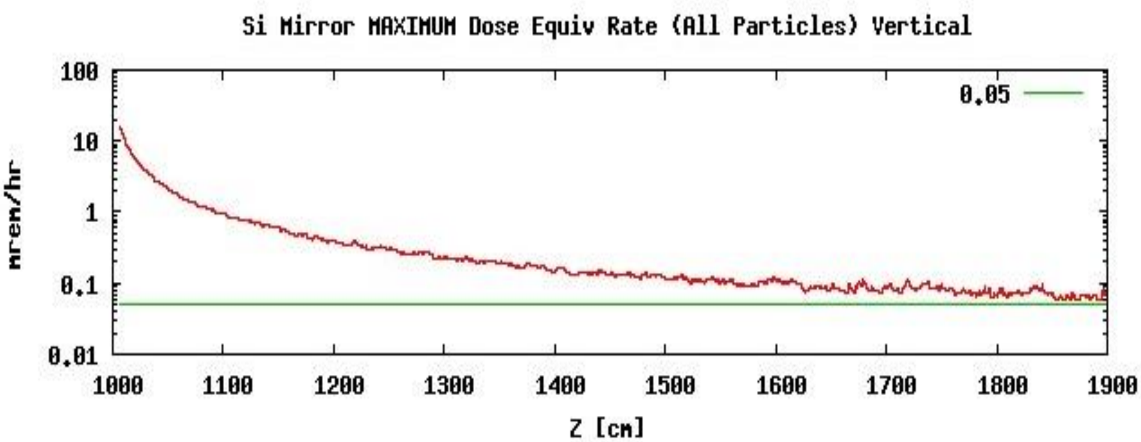


Figure A9.2-6: Maximum dose rate function of the longitudinal coordinate (Z).

For BM/3PW beamlines an exclusion area should extend to 4 m downstream of the enclosure and about 1m laterally (figures A9.2-7 and A9.2-8).

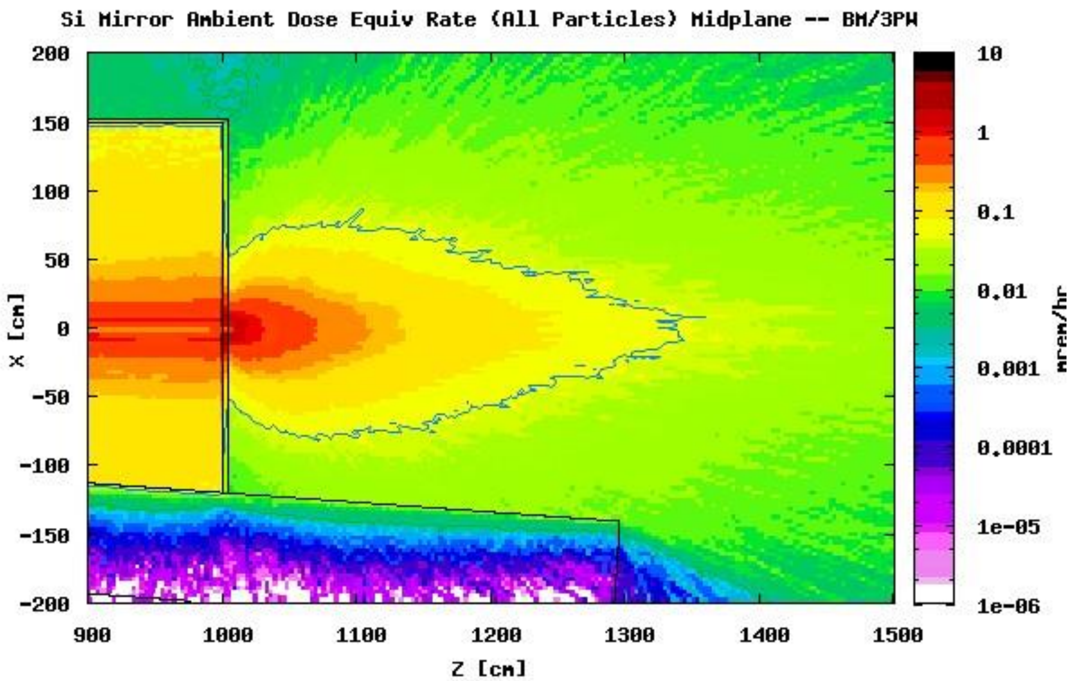


Figure A9.2-7: Dose rates for BM/3PW. The 0.05 mrem/hr contour line is shown in blue.

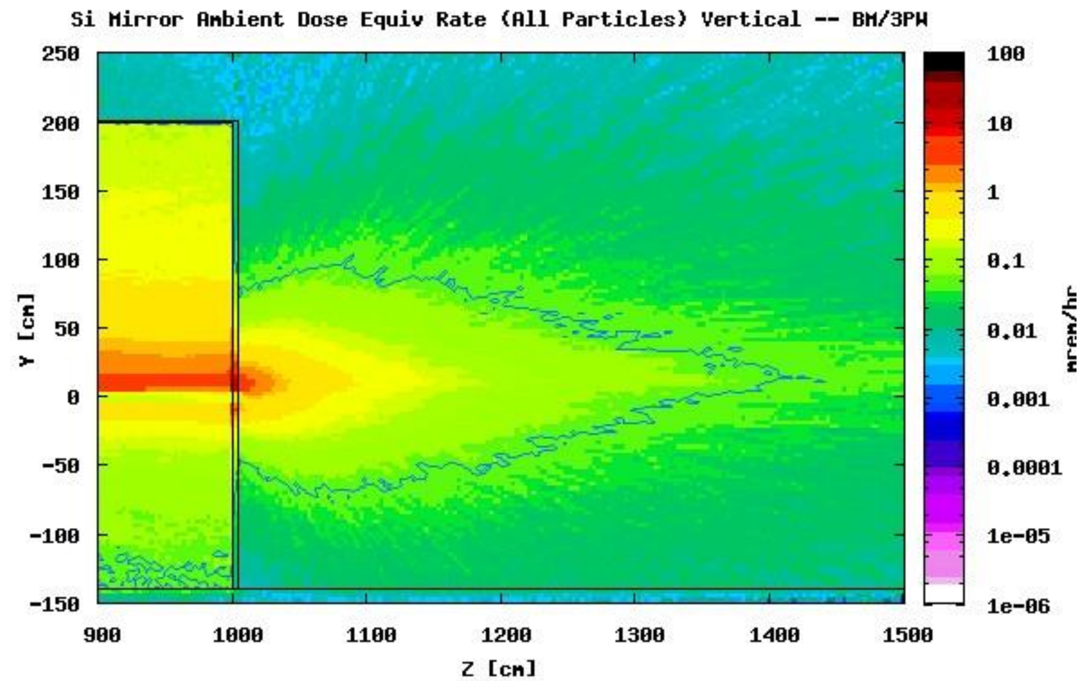


Figure A9.2-8: Dose rates for BM/3PW. The 0.05 mrem/hr contour line is shown in blue.